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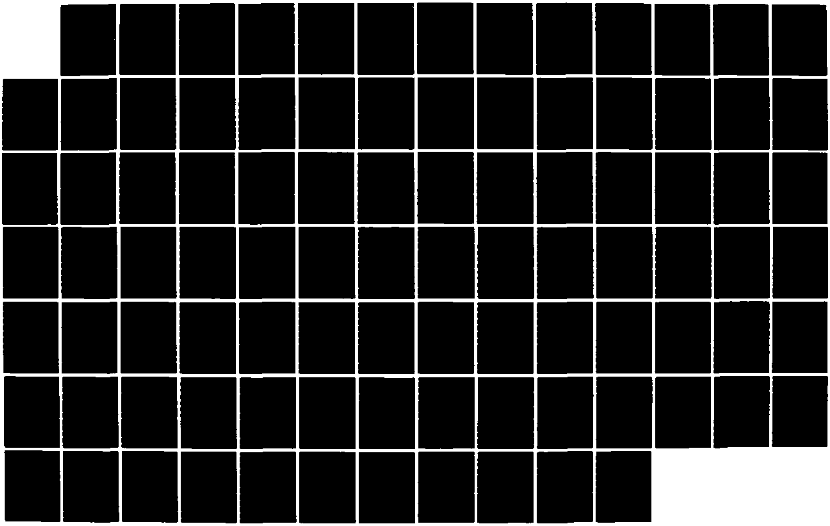

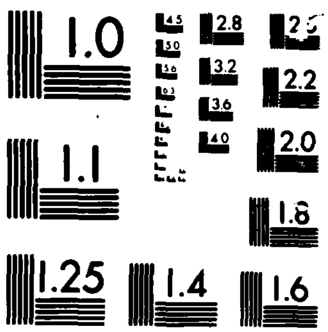

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ABSTRACT

The energy-state approximation was applied to a subsonic, propeller-driven aircraft using both a sawtooth climb analysis procedure and a level acceleration method.

The results showed that energy techniques, i.e., the correlation between sawtooth and level acceleration methods, are a valuable support tool to the previously isolated potential energy (sawtooth climb) method. Data demonstrated a test time savings of approximately seven-to-one with a variance in overall correlation that, although not within acceptable standards, is believed to be reducible with a more dedicated instrumentation selection. Data correlation did suggest very good agreement on best rate-of-climb speed determination. However, this should be an asset in reducing the time previously required for the determination of excess Thrust Horsepower. Further testing, specifically with the level acceleration method, using higher resolution data acquisition equipment (with possibly an accelerometer) would fully demonstrate the extent of unaccountable losses and resulting disagreement between the two methods.

3

THE APPLICATION OF ENERGY TECHNIQUES TO PROPELLER-DRIVEN AIRPLANES

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Douglas Bruce Youngblood

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LIST OF SYMBOLS

a	Subscript signifying ambient conditions
γ	Aircraft flight path angle
α	Angle of attack as measured from zero-lift axis
BHP	Brake horsepower as developed by the engine
c	Angle between thrust axis and zero-lift axis
CIW	Climb, corrected for weight changes
C_L	Coefficient of lift
D	Aircraft total drag - the sum of profile and induced drags
dE_h/dt	Rate of change of specific energy with respect to time
dh/dt	Observed rate of climb
E_h	Energy height or specific energy
E_T	Total energy
F_T	Total aircraft thrust
g	Acceleration due to gravity
h	Geometric altitude
H_p	Pressure altitude
IW	Subscript signifying data corrected to standard aircraft weight
K	Dynamometer torque constant
KE	Aircraft kinetic energy component
MAP	Ambient engine manifold pressure
n	Propeller rotational speed in revolutions per unit time
o	Subscript signifying observed data
OAT	Outside air temperature

PE	Aircraft potential energy component
PIW	Power, corrected for weight changes
P_s	Specific excess power, = dE_h/dt
Q	Engine torque pressure reading
RPM	Engine crankshaft revolutions per minute
s	Subscript signifying standard day conditions and standard aircraft conditions
ssl	Subscript signifying standard sea level conditions
t	Subscript signifying aircraft test conditions
THP	Thrust horsepower, subscripted with (av), (req), and (ex) for available, required, and in excess, respectively, as pertinent to the aircraft maneuver being performed
T/W	Thrust-to-weight ratio
V	Calibrated aircraft velocity
V_i	Indicated aircraft velocity
V_T	True aircraft velocity
V_x	Best angle of climb speed
V_y	Best rate of climb speed
W	Aircraft gross weight
W_s	Standard aircraft gross weight
W_t	Test aircraft gross weight
η	Powerplant efficiency
Ω	Angular velocity of the engine
ΔV_i	Airspeed indicator instrument error correction
ΔV_p	Airspeed position error correction
θ	Temperature ratio, = T_t/T
σ	Density ratio, = $\rho_t/\rho_s = \delta/\theta$

η	Propeller efficiency
δ	Pressure ratio

I. INTRODUCTION

The accurate prediction and verification of weapon system capabilities and performance has always been of prime importance to the aerospace research and development community. In today's world of expensive and time-critical test and evaluation procedures the practicing flight test engineer has an urgent need to use accurate but time-saving techniques. As is well documented, a shortened flight test approach to supersonic aircraft analysis has been used for approximately thirty years employing a study of an aircraft's shifting ratio of kinetic and potential energies. This method uses an independent variable that considers altitude (potential energy) and speed (kinetic energy) separately. This separation enables two flight test methods to be used to demonstrate an energy increase by constant speed climbing or by accelerating at a single altitude. This approach is more suited than the previous method of simply climbing to an altitude to describe an aircraft climb performance. This is because an over-ambitious climb may reduce flight speeds (kinetic energy) to the extent that the aircraft is temporarily nonmaneuverable. This climb would therefore not demonstrate an optimum, usable flight path.

Theoretically, the energy-state approximation has always been applicable to subsonic aircraft. However, the climb of early, relatively slow vehicles consisted of increasing the potential energy of the aircraft, with any changes in kinetic energy being small and, therefore, customarily eliminated from the analysis. With the newer, higher wing-loaded, greater thrust-to-weight ratio, and specifically

jet propelled aircraft came greater climb speeds which legitimized potential/kinetic energy transfers. This ability to interchange kinetic and potential energies made attractive the interchange of altitude and airspeed and led to the use of specific energy and specific energy rate as important indicators of flight capabilities.

Aircraft performance optimizations have been investigated rogorously in past years and have been analyzed using varying parameters. Rutowski [1][1] and Davy [2] each considered the minimum-time and minimum-fuel climb using a graphical approach. Lush [2] and Bryson [3] studied time-to-climb problems using digital gradient methods. Others have studied minimum fuel and minimum time paths, minimum fuel-cruise, and maximum range problems using energy state approaches [1,3,7,8,9,11,1]. Energy management techniques have also been undertaken to optimize tactical and maneuvering performance [14] on military fighter aircraft. This approach has included the design and construction of on-board instruments or systems that attempted to implement the total energy concept at the operational level [15].

This thesis examines the validity of using the energy technique on propeller-driven aircraft during a climb analysis. The study will compare an accepted subsonic aircraft climb analysis method (pure potential energy increase) with an acceleration analysis procedure (pure kinetic energy increase) that has been a subject of criticism when used within a subsonic flight test program because of aircraft power limitations and flight test assumptions.

[1]Numbers in brackets refer to similarly numbered references in the Bibliography.

II. BACKGROUND

The climb performance of an airplane, whether subsonic or supersonic, is generally described in terms of its maximum sea level rate of climb, its service or operating ceiling, and the time to climb to a given altitude. The most feasible approach to climb performance testing is achieved when one considers the time to climb to a given energy level rather than to a given altitude. If an airplane approaches an altitude with a very low airspeed, an additional amount of time is required to reach a usable maneuvering flight velocity. The total energy concept allows an ideal (and close to actual) flight path to be flown and can provide a climb schedule that permits an aircraft to be maneuverable at all times.

Although "energy height" management, or the total energy concept, is viable for subsonic, propeller-driven aircraft [6], the best rate of climb for propeller-driven aircraft was always obtained by using a "sawtooth" climb method of flight testing. The sawtooth climb was used since the total energy concept for propeller-driven aircraft is "not as satisfactory for piston engine aircraft as for jets" [6]. This was demonstrated by examining the differences in flight path speeds of propeller and jet engine aircraft [6]. In most cases the flight path speeds for jet aircraft are much greater than for propeller-driven aircraft due to the inherent propulsive characteristics of the propeller and the limitation of brake horsepower available from an internal combustion/reciprocating or turbine engine. This variance in propulsive capabilities and resulting differences in speeds are directly

linked to the aircraft's limited thrust-to-weight (T/W) ratio. The conservative T/W ratios of most propeller-driven aircraft did not permit rapid transfers of engine power for altitude or velocity and made questionable the accuracy of exchanging the two components of kinetic and potential energies. The value and correctness of the total energy approach to subsonic flight vehicles arose from the concern that the technique would incur excessive losses due to complicated and possibly unaccountable pilot/aircraft interactions. The trading back and forth of the energy components is greatly influenced by pilot technique and aircraft movements during the lower speed flights with possible losses comprising a large percentage of the total power provided during a test.

The purpose of conducting either sawtooth or acceleration runs is to determine the variation of excess power with airspeed. In sawtooth climbs the resulting data are used to evaluate climb characteristics. In acceleration runs the data may determine climb characteristics, level acceleration traits, maximum level flight airspeed, and estimates of level flight turning performance. In addition to the expanded information available from the level acceleration test procedure the method has a dramatically shorter flight procedure.

III. THEORY

An energy state approximation for an aircraft is most appropriately begun with an examination of the production and use of energies as the vehicle is translated or rotated while performing its mission. For a propeller-driven airplane the energy for propulsion, derived from the heat content of the stored fuel, is initially converted to mechanical energy by the powerplant. The effectiveness of this transfer is the product of the powerplant propulsive and thermal efficiencies and is termed the overall powerplant efficiency. The overall efficiency and resulting engine power capability may be strongly affected by other variables after the engine is designed. These include intake and exhaust system conditions, cooling tendencies, and secondary engine-driven devices. The basic power equation for an internal combustion engine using a torquemeter testing procedure may be represented as:

$$BHP = Q[RPM][K] \tag{1}$$

The test procedure for determining brake horsepower of an internal combustion engine in flight include the following methods:

1) Engine Power Charts
2) Torquemeter Method
3) Fuel Flow Method

All three are reviewed within the AGARD Manual [2,5,6] and by Kimberlin [18]. Each have strengths and hinderances which may preclude them from being used by test organizations. The tradeoffs of all three techniques are complexity versus accuracy. The previous listing presents in sequence the simplest and least accurate procedure (power chart)

to the most accurate and complicated method (fuel flow). Interested readers should find that References [2,5,6] and [18] explore the systems used in flight test organizations. The method used within this thesis was the engine power chart procedure chosen because of its simplicity.

With propeller-driven aircraft the energy acquired through the burning process is converted to thrust by rotating airfoil(s) and it is this force that is used to propel the aircraft. The effectiveness of this transfer of brake horsepower to thrust force is dependent on the changing efficiency of the propeller as the airscrew blades change pitch and rotational speeds, the downstream flow resulting from the aircartt shape, the aircraft's forward speed and operating flight altitude. At constant altitude the maximum brake horsepower available from the engine is virtually independent of forward speed and is therefore considered constant. The efficiency of the propeller, however, is not. At low speeds, the efficiency of a variable pitch propeller increases quickly with velocity. This tendency is consistent even at higher speeds, although the increase is not as rapid. The efficiency of the propeller is defined as the ratio of the power output to the power input. Their relationship may be fully understood by the following equation:

$$\eta = Power_{out}/Power_{input} \tag{2}$$

$$\eta = F_T/[\Omega]Q = F_T V/[2(\pi)n]Q$$

Thus the overall thrust horsepower obtainable from a reciprocating engine and propeller combination increases with speed. These varying

interaction effects greatly hinder the flight test determination of the thrust/drag of an aircraft, both of which are the cornerstones of required input parameters to quantify an aircraft's performance capabilities [18]. Any thrust which is in excess of the thrust required to balance the sum of profile and induced drags, or total drag, may be used to increase the total energy of the aircraft. An aircraft's total energy may be expressed as:

$$E_T = PE + KE = Wh + WV^2/2g = W(h + V^2/2g), \text{ or}$$

$$E/W = h + V^2/2g \tag{3}$$

In calculating the differing optimal flight paths of an aerospace vehicle, varying dynamic models may be used to describe the aircraft motion. These models may range from a simple point-mass, quasi-steady representation to a more complex study involving aircraft deflections, changing weight (and the corresponding center of gravity) or other variables. Unfortunately, consideration of every possible aircraft dynamic effect would lead to problems of such computational complexity that the effort required to obtain their solution might never be warranted for preliminary performance estimations. It is at this point that many authors of performance optimization techniques differ in their approach or even acceptance of subsonic aircraft with the total energy approximation. Bryson, et al. [3] use a quasi-steady approximation on subsonic aircraft and an energy-state (energy-climb) approximation with supersonic aircraft. Their argument is that with subsonic aircraft kinetic energy cannot be traded back and forth in zero time without loss of total energy. They state that only with an aircraft

flying at supersonic speeds is the kinetic energy comparable to its relative ground gravitational potential energy. Ardema [19] examined the energy state, two-state, and modified two-state approaches and outlined the improvement in accuracy of each approximation procedure, along with their respective penalties in added complexity. The two-state approximation treats both velocity and altitude as state variables, making them continuous, and uses the flight path angle as the control variable. The modified two state is an extension of the two-state method but incorporates drag due to lift and accounts for the time required to change flight path angle. The next most ambitious estimation is to treat velocity, altitude, and flight path angle as state variables with angle of attack as the control variable, and mass approximated as a function of time [3]. Varying approaches may be undertaken in minimum-climb analysis; however, the scope of this examination was a possible flight test analysis/validation of the energy technique for propeller-driven aircraft. Interested readers should refer to the papers listed in the bibliography, as individual techniques are outlined with their differences and limitations examined in detail.

This analysis is an energy state/point-mass study of a propeller-driven airplane that includes the acceleration component. In the study the energy is treated as a state variable and altitude or velocity is used as a control variable. In this method, necessary boundary conditions are satisfied by adjoining constant energy paths to the optimal path. This widely used approximation, while believed optimistic with calculated climb times by Ardema [19], has been found to be adequate

for the performance prediction in a vertical plane and eliminates unacceptable computational difficulties and expenses. Referring to Figure 1, the equations of motion for this model are:

$$E_T = PE + KE = Wh + (W/2g)V^2 \tag{4}$$

Dividing by the weight and defining energy height yields:

$$E_h = E_T/W = h + V^2/2g \tag{5}$$

This energy height, or specific energy, may be interpreted as the altitude which could be attained if all the kinetic energy were converted to potential energy, or the maximum airspeed that could be attained if all the potential energy (height) was converted into kinetic energy. This assumes that the aircraft is rigid and so a point-mass analysis may be undertaken.

To fully define an aircraft's performance capabilities, however, it is necessary to demonstrate its ability to change its energy level in a given time. Differentiating Equation (5) with respect to time gives:

$$dE_h/dt = dh/dt + (V/g)(dV/dt) \tag{6}$$

Using a small angle approximation for the aircraft's angle of attack, and zero-lift to thrust axis variation, enables the following assumptions:

$$\sin(\alpha + c) = (\alpha + c) \text{ and } \cos(\alpha = c) = 1$$

Using an assumption that thrust is along the flight path, and that the aircraft mass is constant during the individual data runs, simplifies testing procedures. These assumptions make possible an analysis with

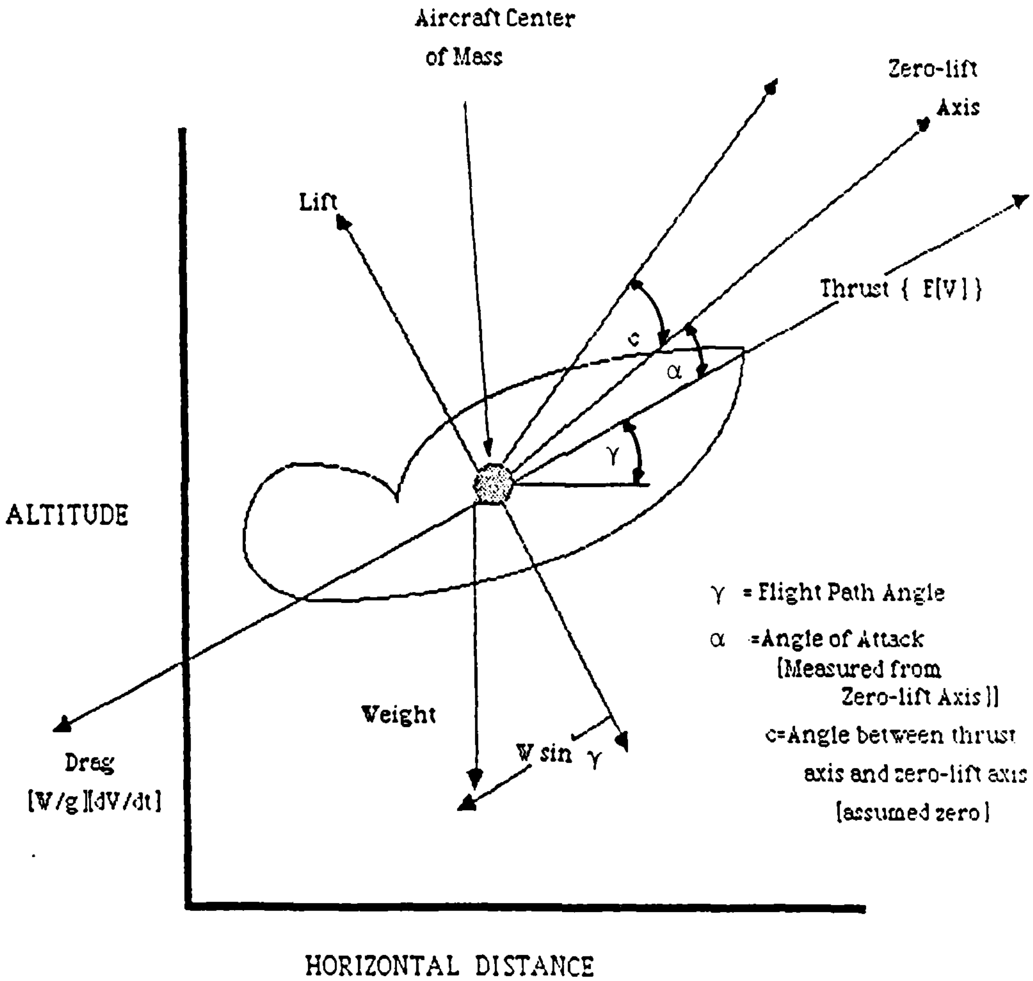

Figure 1. Free Body Diagram with Corresponding Forces

existing aircraft and test equipment. The supposition that thrust is along the aircraft flight path eliminates complications encountered when lift other than that produced by the wing from airfoil pressure interactions (i.e., thrust vectoring) is taken into account. This distinction in the ways lift may be derived is critical during the low-speed operating envelope of the airplane, when induced drag (a parameter dependent on coefficient of lift) is the predominant influence on an aircraft's performance. With these assumptions it follows that:

$$F_{total} = d(mV)/dt = ma = (W/g)(dV/dt) \qquad (7)$$

$$F_{total} = F - D - W \sin \alpha = (W/g)(dV/dt) \qquad (8)$$

Rearranging (8) yields:

$$\sin \alpha = (dh/dt)/V \qquad (9)$$

Substituting (9) into (8) and multiplying by V produces:

$$dh/dt + (V/g)(dV/dt) = [V(F - D)]/W = dE_h/dt \qquad (10)$$

The right-hand side of the equation is the specific excess power. The two left-hand terms show the relation of linear acceleration and vertical speed or rate of climb.

If the thrust and drag characteristics of the airplane are known, Equation (10) may be used to determine the rate of change of specific energy by either demonstrating the maximum acceleration at a constant altitude or by performing a constant speed maximum rate climb (both with full power engine settings) and thereby demonstrate the performance capabilities of the aircraft. Using a succession of different altitude values, curves as in Figure 2 may be constructed. Note that as altitude

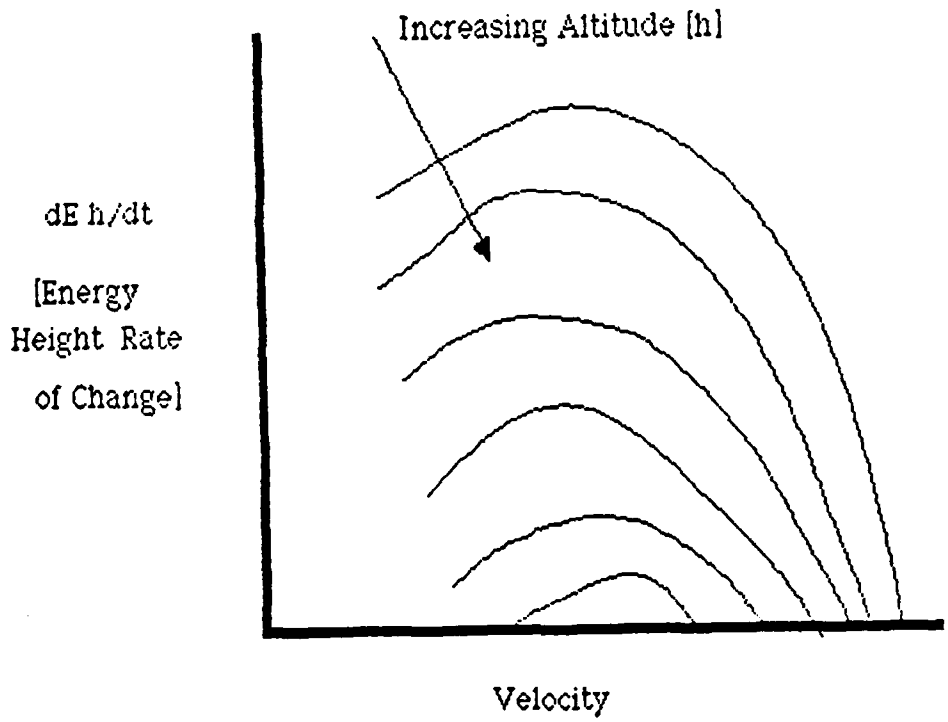

Figure 2. Subsonic Aircraft Specific Excess Power versus Airspeed Characteristics

increases the excess thrust falls and dE_h/dt is reduced at all values of velocity. The specific excess power reduction occurs because brake horsepower, and therefore thrust horsepower, is dependent upon air density. A review of elementary physics reaffirms that altitude (pressure) and temperature are key parameters in determining the air's mass-to-volume ratio. By repeatedly selecting differing values of dE_h/dt and plotting their corresponding values of h versus V the graph of Figure 3 may be constructed. Superimposed on this figure is a set of curves showing the variation of h with V at constant energy heights, obtained by taking a particular value of energy height and substituting it in Equation (5). Also placed on this figure is a hypothetical supersonic aircraft flight regime. As is well expounded by Rutowski [1], and may be visually obvious after examination, this elongated performance envelope makes attractive an energy approach to high performance aircraft, since higher energy levels are obtainable past the transonic drag rise. Interestingly, to achieve the minimum time path, a supersonically capable aircraft would have to, in theory, ascend subsonically to a given altitude, then go supersonic by diving along the specific energy curve, and continue supersonic through a climb until its maximum energy point is attained. This optimum flight plan, of course, does not hold completely true in practice. Construction of Figure 3 assumes that the aircraft is infinitely maneuverable, and that kinetic and potential energies can be instantaneously interchanged without any losses whatsoever, and this is understandably incorrect. However, as was the initial intent of this thesis analysis, the method will give an acceptable indication of the aircraft's performance

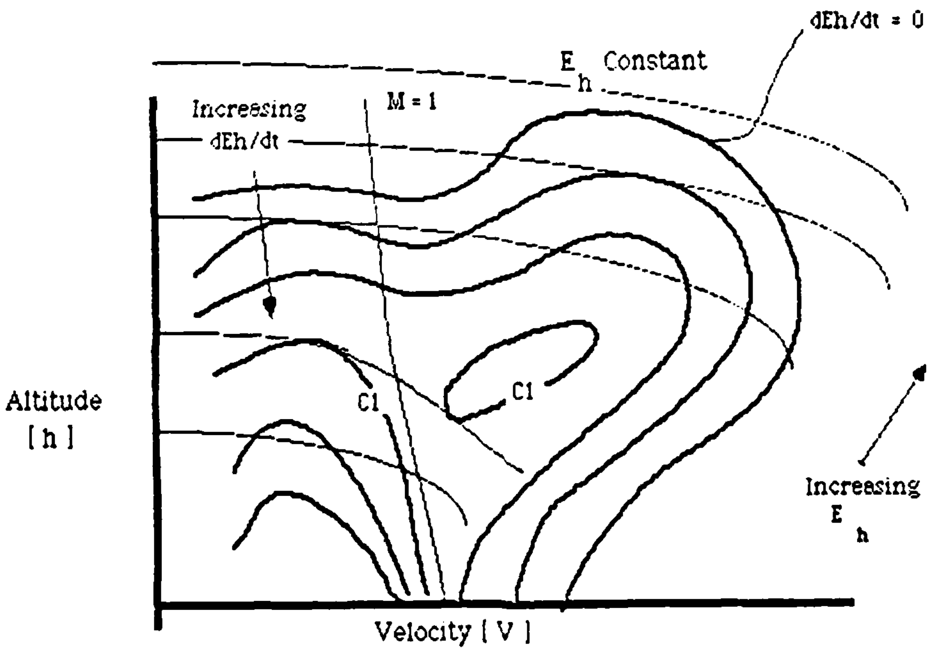

Figure 3. Specific Excess Power versus Airspeed for all Aircraft -- with Affecting Parameters

(i.e., the best practical flight plan), which will often approximate the ideal.

As previously stated, a more classical and rigorous climb equation can be used which takes into account such variables as changing aircraft shape and unsymmetrical thrust to longitudinal acceleration vectors. However, the resulting complex climb equation would require a numerical analysis approach using a calculus of variations method or a similarly theoretical analytical or computational approach [19]. Unfortunately, that approach does not provide an intuitively physical understanding of the model and therefore is not within the scope of this study.

IV. SAWTOOTH CLIMB METHODS

The sawtooth test procedure is the oldest flight test method in current use to determine the variation of excess power with airspeed. This flight method consists of flying in a steady climb while maintaining a constant calibrated airspeed and a full-power engine setting. In essence, this vector approach attempts to maintain a constant calibrated airspeed, thereby eliminating the acceleration term from Equation (10) while increasing by a maximum amount the aircraft's potential energy component.

The right-hand side of Equation (10), after multiplication by the weight term, may be expressed as total thrust horsepower available to the aircraft minus the required thrust horsepower needed to overcome aircraft drag. This quantity, as shown in Figure 4, is the thrust horsepower in excess and is the usable surplus power capable of translating or rotating the aircraft. These curves define the aircraft's total performance capabilities. Equation (10), after weight multiplication and elimination of the acceleration term, results in:

$$W(dh/dt) = THP_{in\ excess} \tag{11}$$

The relationships of Figure 4 may be understood through the following equation:

$$THP_{av} = THP_{req} + THP_{in\ excess} = (BHP_{av})\eta_p \tag{12}$$

The brake horsepower available and the propeller efficiency are key parameters to overall performance. Understandably, the brake horsepower supplied by the engine to the propeller is limited by its

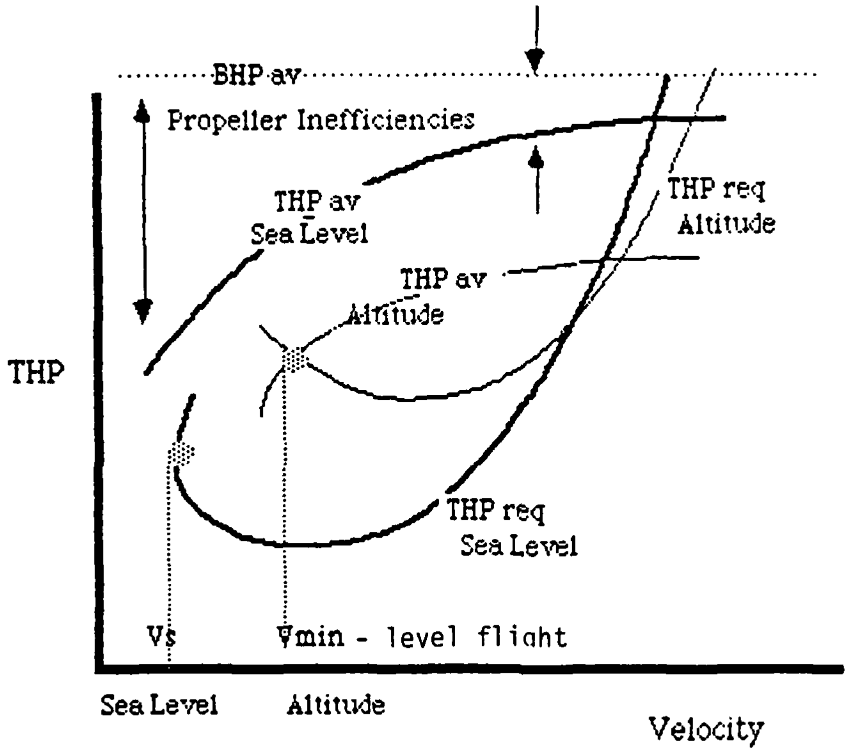

Figure 4. Total Performance Envelope for the Piston Engine Aircraft

design. The propeller is not a perfectly efficient mechanism, as free-stream density and velocity affect its capabilities. Because of these density and velocity changes the absolute efficiency of the propeller is never perfectly calculated. Therefore, thrust horsepower available, which is highly dependent on propeller efficiency, is difficult to determine.

As previously stated the $THP_{in\ excess}$, hereafter denoted THP_{ex}, may be obtained from either a sawtooth climb or level acceleration analysis. A THP_{ex}-versus-Equivalent Airspeed plot, as shown in Figure 5, demonstrates how the excess power varies with airspeed. The Rate of Climb versus Equivalent Airspeed as shown in Figure 6 may then be constructed using Equation (11). From it may be determined the Best Angle-of-Climb Speeds (speed for maximum angle of climb), and Best Rate-of-Climb Speeds. The speed for maximum angle of climb is found by drawing the tangent from the origin to the excess power-versus-velocity curve. The best rate-of-climb speed is the velocity that corresponds to the maximum excess power (i.e., the top point on the excess power-versus-power curve). Extracting data from this figure enables a plot of Best Rate-of-Climb Speed versus Altitude and Best Angle-of-Climb Speed versus Altitude to be constructed. The observed climb performance is strongly affected by variations in power (or thrust) available and by changes in aircraft total weight. In propeller-driven aircraft, variations in ambient temperature create changes in power, or thrust available, that are virtually constant with airspeed change. These power available changes therefore influence just the value of the rate of climb and not the airspeed at which it occurs. Changes in aircraft

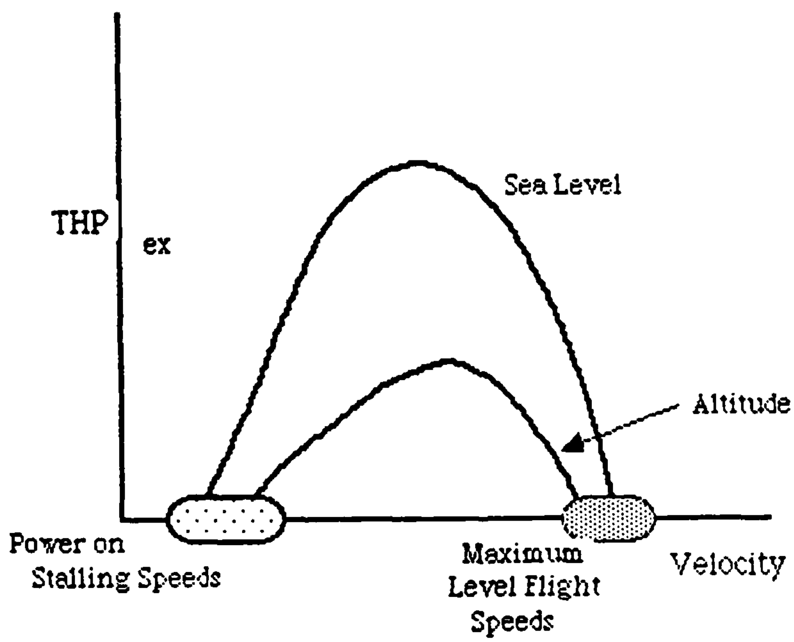

Figure 5. Specific Excess Power versus Airspeed for Subsonic Aircraft - with Minimum and Maximum Speed Capabilities Highlighted

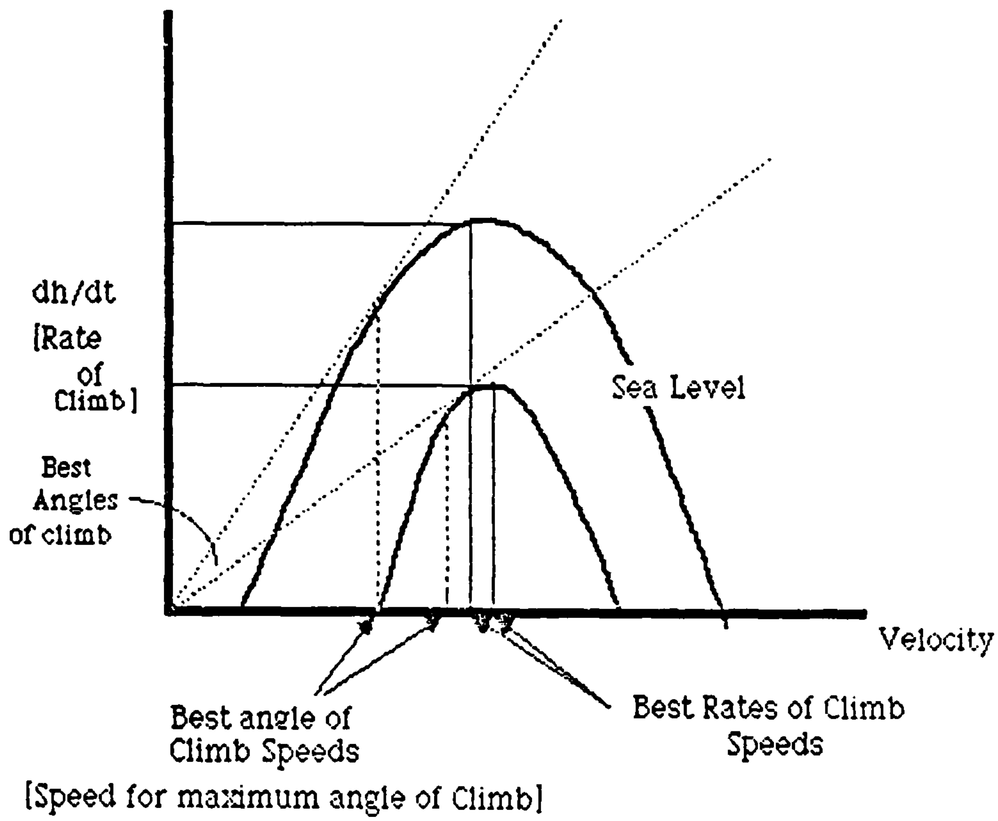

Figure 6. Rate of Climb versus Airspeed for Subsonic Aircraft - Showing Altitude Effects and Derivable Performance Parameters

weight influence climb performance capabilities by increasing the induced drag. This is because weight changes affect the influence that C_L has on an aircraft through its induced drag component. As shown in Figure 4, the induced drag component alters the power/thrust required curves and thus affects the airspeeds at which maximum rate of climb and maximum climb angle occur. Both the minimum drag and the minimum drag speed tend to increase with aircraft weight. Fortunately for low fuel consumption (i.e., normally-aspirated reciprocating engine) aircraft these changes are trivial if small deviations from standard aircraft weight are maintained.

Although the actual flight technique involved with sawtooth testing is not difficult, it is important that the test runs be accomplished in calm air, with neither wind gusts or temperature inversions.

The sawtooth technique involves performing a stabilized climb and was accomplished in the following manner:

1) At an altitude below the test altitude (300 to 500 feet below) the aircraft is trimmed to maintain the indicated airspeed which is desired in the climb analysis.

2) While maintaining the desired airspeed, the climb is initiated through throttle advancement until the rated power of interest for the analysis is attained. To minimize wind effects each climb is repeated in opposite directions and always conducted crosswind. It should be noted that it is not imperative that the climb airspeeds exactly match the planned airspeed goal. As stated in Reference [4], an attempt should be made to attain the smallest deviation in airspeed possible, with a one knot spread around the initial value as a goal. To ensure good results it is also suggested that the airspeed at the end of the climb be identical with the airspeed at the beginning of the climb. This aids in demonstrating the overall linear tendency of the data.

3) Data are recorded every thirty seconds from test band entry to test band exit. Data consist of engine speed (RPM), engine torque pressure (Q) or ambient engine manifold pressure (MAP), outside air temperature (OAT), altitude (h), time (t), and airspeeds (V). Refer to Figure 7.

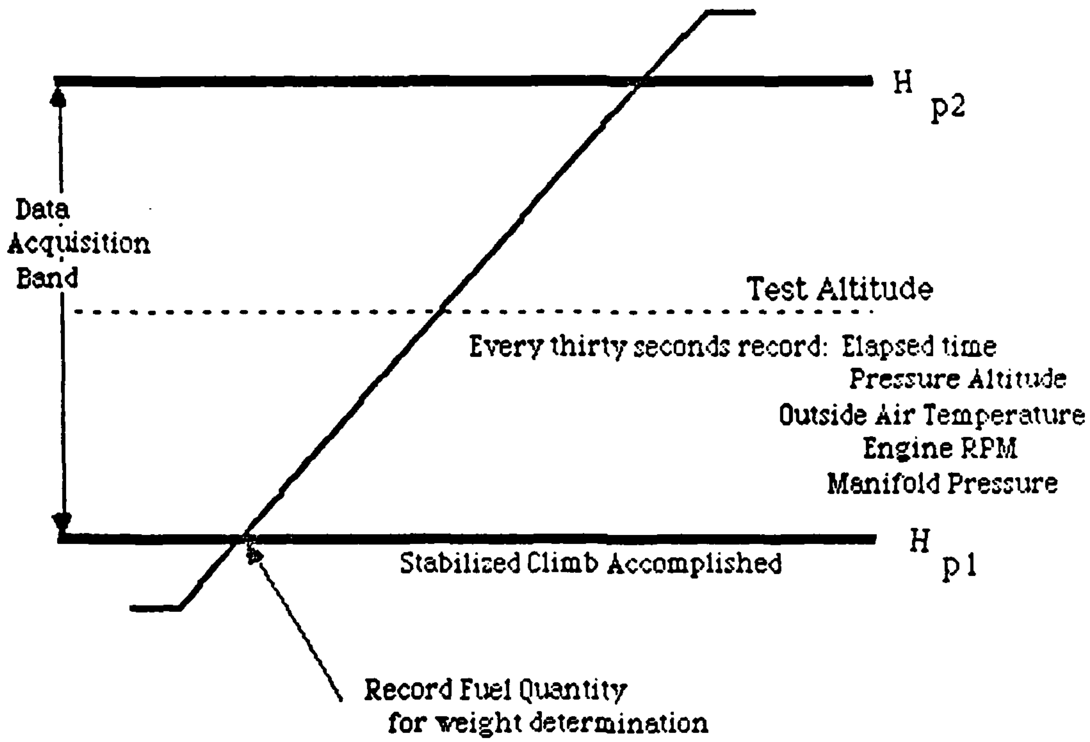

Figure 7. Sawtooth Climb Flight Procedures

4) Procedures 1 through 3 are repeated using differing airspeeds to gather sufficient data to map complete single altitude performance capabilities. Different altitude bands are then accomplished in the same manner.

This flight procedure demands a smooth pilot flying technique without wasteful control surface deflections and no outside energy input from temperature or dynamic wind gradients. The effect of parameters which change thrust or weight, both of which influence the time to climb, should be understood.

After gathering data, plots of pressure altitude versus time are made for each airspeed and altitude as shown in Figure 8. Plots of Rate of Climb versus Altitude, per airspeed, are then constructed using the slopes of the averaged two-direction data runs from this figure. The complete set of plots were previously shown in Figure 6. As stated earlier, this figure will provide the Best Angle-of-Climb Speed (V_x) and Best Rate-of-Climb Speed (V_y), respectively, as shown in Figure 9.

With all raw flight measurements, the plotted data must be reduced into usable information. The reduction methods that are accepted by the Federal Aviation Administration (FAA) for propeller-driven aircraft are defined separately for constant-speed and fixed-pitch propellers. Each of these has their limitations and specified applications. Therefore, a decision as to which method to use must be made. The three methods are:

1. PIW vs CIW Method
2. Density Altitude Method
3. Equivalent Altitude Method

Of these three methods, only the density altitude procedure is limited

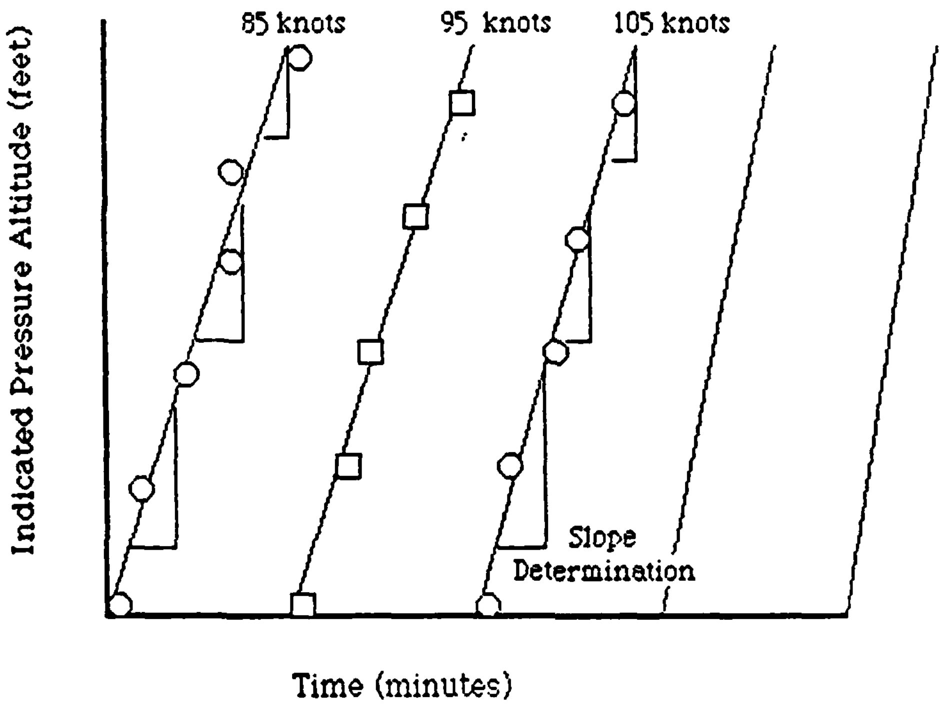

Figure 8. Indicated Pressure Altitude versus Time for Single Altitude Band at Varying Indicated Airspeeds

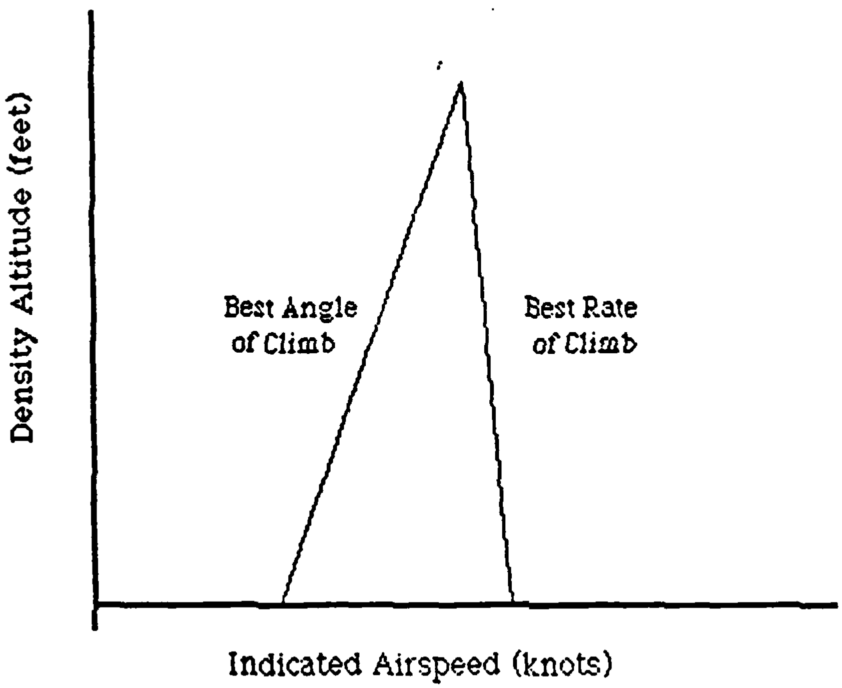

Figure 9. Best Angle and Best Rate of Climb Speeds as Derived from Figure 6

to a constant speed propeller. On constant speed propellers, the blade pitch is designed to vary automatically and maintain a constant rotational speed. The benefit of constant speed/variable pitch propellers is that they enable an elongated band of higher efficiency to be obtained. This is accomplished by changing the blade angle of attack during changes in airspeed, thereby expanding the optimum propeller efficiency peak over several velocities. The fixed pitch propeller, however, is only capable of performing at optimum efficiency at a single airspeed.

Depending on the reduction procedure used, the reduced data may need to be expanded into a form that is usable to the pilot in varying flight conditions. This expansion is required because some reduction procedures are limited to standard sea level test conditions at standard weight. Of the three FAA reduction methods, only the PIW versus CIW method requires expansion to non-standard conditions. Although all three methods are relatively straightforward, the Density Altitude Method requires that an estimated propeller efficiency be chosen and iterated within the reduction procedure. This estimate can add to the complexity and uncertainty of the results. The iteration requirement, coupled with the fact that the PIW versus CIW procedure is the most familiar to the author, prompted it to be the method used in this study. A synopsis of the PIW versus CIW data analysis technique with applicable equations is presented on Figure 10.

While sawtooth climbs have been used for many years and, in fact, are the mainstay of the FAA test procedures, there are many disadvantages associated with this technique. The climb technique is not

Acquire raw/indicated data to include: Airspeeds

Elapsed Time (for weight determination)

Outside Air Temperature

Pressure Altitude

Manifold Pressure

Engine RPM

Calculate aircraft test weight for each climb run and determine each dH/dt (obs) from individual indicated pressure altitude versus time plots.

Reduce observed rate of climb to values of Piw and Ciw using the following equations:

$\Theta = Tamb/288.16$ Tamb in degrees K

$Tamb = OAT + 273.16$ OAT in degrees C

$\sigma = \delta/\Theta$ $\quad$ $BHPt = BHPc\,[Ts/Tamb]^{1/2}$

$BHPiw = [BHPt(\sigma)^{1/2}]/[Wt/Ws]^{3/2}$

$R/C\ tc = [(R/C\ obs)(Tamb)]/Ts$

$Ciw = [(R/C\ tc)(\sigma)^{1/2}]/[Wt/Ws]^{1/2}$

Plot Piw versus Ciw and expand to standard day conditions using the procedures as exhibited with the raw data.

Figure 10. PIW versus CIW Reduction and Expansion Procedures for the Sawtooth Climb Method

practical with high rate-of-climb aircraft since a large altitude range must be covered on each climb to acquire acceptable data. Also, the data may be affected by pilot inconsistencies and wind gradients (which may be alleviated through crosswind flight paths). Of the above mentioned problems, the latter is objectionable enough to be the primary driving force in studying the level acceleration method for propeller-driven aircraft.

V. LEVEL ACCELERATION METHODS

The level acceleration test procedure simplifies or eliminates several of the problems associated with sawtooth climbs. The technique's greatest shortcoming is that a higher level of skill is demanded of the pilot. However, this can be remedied through practice of the test technique.

The flight procedure in the level acceleration test consists of maintaining a constant altitude while smoothly accelerating the aircraft from its near minimum airspeed to the maximum level flight air speed. This procedure yields a specific energy increase by maintaining constant potential energy while increasing the kinetic energy. The assumptions are that no thrust is diverted to generate lift, and that the gross weight of the aircraft does not change appreciably during the data run. A well executed flight using an aircraft with a low fuel consumption reciprocating engine meets these conditions.

Returning to Equation (10) and holding the height constant produces the general equation:

$$THP_{ex} = (W/g)(dV/dt)V_T \tag{13}$$

The acceleration term, (dV/dt), may be obtained for each airspeed from the line slopes of true airspeed (V_T)-versus-time plot(s) for each altitude run. Having this information, data reduction may be undertaken. Equation (13) may be manipulated for propeller-driven aircraft analysis by using:

$$THP_{ex} = [(W_T/g)(dV_t/dt)(V_T)/550] \tag{14}$$

$$THP_{ex\ (IW)} = (THP_{ex})(\sigma)^{1/2}/(W_T/W_S)^{3/2} \tag{15}$$

$$dh/dt = THP_{ex\ (IW)}\ (550)(60)/W_S \tag{16}$$

By plotting rate-of-climb versus airspeed as in the sawtooth climb method (see Figure 6), we may obtain both maximum rate of climb and climb speeds. A synopsis of the test procedure and the equation involved are presented on Figure 11.

The level acceleration flight test procedure is a nonequilibrium test point method capitalizing on the elimination of the constant height term of Equation (10) to determine specific excess power, (P_S). This method, like the sawtooth climb procedure, takes into account changes of thrust made available from the powerplant but assumes that the propeller is operating at an optimum efficiency. This assumption is not as fundamentally acceptable as it is in the climb technique due to the variance in airspeed (and therefore propeller efficiency) as the aircraft accelerates. While it would be convenient to assume that the propeller is pitched to acquire the optimum efficiency, in reality only a close approximation can be achieved by the twisting mechanism.

The procedure consists of:

1) At the test altitude of interest, and as close to V_{min} as possible, full throttle is applied to produce the maximum acceleration along the longitudinal axis.

2) While holding level flight through constant retrimming of the aircraft, the data consisting of h_{pi}, V_i, t, OAT_i, RPM, MAP, and fuel are recorded continuously.

3) The procedures are repeated at other altitudes, as in the climb technique, to fully define performance boundaries.

FLIGHT TEST REQUIREMENTS

At Vmin airspeed record Outside Air Temperature and Aircraft Weight

After full throttle initiation record elapsed time at each 5-10 knot indicated airspeed increase. Record times from mimimum stable flight speed to maximum level flight speed. Record Engine RPM and Manifold Pressure at run conclusion.

Repeat Level Acceleration Runs at each altitude in opposite directions

DATA INTERPRETATION

Plot TAS versus Time and obtain slopes. Calculate Thrust Horsepower in Excess [THPex] and Thrust Horsepower in Excess weight corrected [THPex wc] using the following equations:

$$THPxc = [Wt/g][dV/dt][TAS]/550$$

$$THPxc\ wc = [THPxc]/[Wt/Ws]^{3/2}$$

DENSITY ALTITUDE DETERMINATION

Calculate density ratio for each altitude and determine density altitude of each test run using the following equations:

$$\theta = Tt/Tssl = [OAT + 459.7]/518.7$$

where: OAT is in degrees F 518.7 is Tssl in degrees R

$$\delta = Pt/Pssl = [1.0 - 6.87535 \times 10^{-6} (Hpc)]^{5.2561}$$

$$\sigma = \rho t/\rho ssl = \delta/\theta$$

RATE OF CLIMB DETERMINATION

Plot corrected Thrust Horsepower in Excess versus Calibrated Airspeed and determine maximum THPex wc for each altitude and calculate the maximum rate of climb at each density altitude using the following equations:

$$dh/dt = [THPex\ wc][550][60]/Ws$$

where: dh/dt is rate of climb in feet/minute

Figure 11. Data Reduction Procedure as Used by the Level Acceleration Method

As with the sawtooth climb procedure, the level acceleration method attempts to measure an aircraft's total energy increase (in this case kinetic energy) in an effort to demonstrate the aircraft's performance. Although good pilot technique and automated data acquisition are required to gather acceptable data, the method's shortened flight times and increased data are impressive. Pilot technique is pertinent because the test method demands the aircraft be flown from near stall to a maximum level airspeed while maintaining a single altitude. This minimum to maximum condition is attained by the aviator introducing a full throttle setting at near the stall. Recorded data runs are required since the rotation of the aircraft from the near stall condition to a level attitude changes flight parameters rapidly. The increase in power and resulting aircraft rotation additionally inhibits a precise, constant altitude to be maintained. This change in altitude greatly influences the acceleration.

VI. TEST PROCEDURES

The data used to compare the sawtooth climbs to level acceleration runs were acquired from the Davidson and Hodgson 1958 Cessna 310 report [16] and the August 1985 flight test data from The University of Tennessee Space Institute's (UTSI's) Cessna 310 (#N22UT) aircraft. Data comparisons were initially performed between the 1985 UTSI sawtooth climb and level acceleration runs. The older USAF data from Reference [16] were included following complete reduction and expansion of the newer data. It was not used as a guideline.

The Cessna is a twin-engine, all metal, low-wing monoplane with fully retractable tricycle landing gear. It is capable of comfortably seating two crew members (dual controls) and two passengers. The aircraft is powered by two six-cylinder, horizontally-opposed, air-cooled, normally-aspirated Continental 0-470-M engines rates at 240 horsepower each at sea level. Each engine supports a two-bladed Hartzell HC 82XF-2/8433-4 constant-speed, full-feathering propeller. A full listing of the aircraft's specifications is presented in Figure 12.

The UTSI flight test plan and corresponding analysis were designed to coincide as closely as possible with the velocity, altitude, and weight variables of the 1958 Air Force report. Although sawtooth and level acceleration methods can be performed with any landing gear and flap configurations, this study examined only the applicability of the energy technique in a clean configuration. The entire UTSI flight program consisted of eleven flights and was designed to acquire the

Aircraft Dimensions

Design information and general dimensions of the airplane, taken from Cessna specification Number 15015, are as follows:

Airplane:

Length	26.98 ft
Height	10.46 ft
Span	35.77 ft
Weight - max. take off	4830 lb

Wing Group:

Area (Total)	175 sq ft
Type	Full cantilever
Chord:	
at root	67.5 in.
at construction tip	46.18 in.
mean aerodynamic	61.0 in.
Airfoil (centerline)	NACA 23018
Airfoil (tip)	NACA 23009
Airfoil (nacelle)	NACA 23015
Incidence (root)	+ 2 deg 30 min
Incidence (tip)	- 0 deg 30 min
Dihedral	5 deg
Taper Ratio	1.517
Aspect Ratio	7.3

Flap:

type	Split
area	22.9 sq ft
angular travel	45 deg down

Aileron:

Area (total)	13.4 sq ft
Aileron tab area	0.55 sq ft
Span	69 in.
Movement (aileron)	20 deg up, 20 deg down
Movement (aileron tab)	20 deg up, 20 deg down

Empennage Group:

Stabilizer	
span	170.0 ft
area (to elevator hinge)	32.15 sq ft
chord MAC	41.1 in.

Empennage Group - continued:

airfoil (root)	NACA 0009
airfoil (tip)	NACA 0006
incidence, normal	-1 deg 45 min
dihedral	0 deg
aspect ratio	5.2

Elevator:

area (total)	22.10 sq ft
span	17.0 ft
trim tab area	1.25 sq ft
movement (elevator)	25 deg up, 15 deg down
movement (trim tab)	20 deg up, 28 deg down

Vertical Tail:

Area (total)	25.86 sq ft
Fin area (including dorsal)	14.08 sq ft
Rudder area(total)	11.78 sq ft
Trim area	0.66 sq ft
Chord MAC	50.7 in.
Airfoil (root)	NACA 0009
Airfoil (tip)	NACA 0006
Aspect Ratio	1.55
Movement(rudder)	25 deg each side of neutral
Movement (rudder tab)	26 deg left, 20 deg right
Fuel Capacity(total)	132-1/4
Fuel Capacity(UTSI) Aircraft (Usable)	100
Oil Capacity (each engine)	3 gallon

Figure 12. Cessna 310 General Aircraft Specifications

most reliable data with the limited funds available for testing. The test program studied and mapped the aircraft performance envelope at 3000, 5000, 8000, and 10,000 feet altitudes for both sawtooth climb and level acceleration methods. The sawtooth climb procedure included climbs at 85, 95, 105, 115, and 125 knots indicated airspeeds.

Both 1958 and 1985 sawtooth climb data were obtained using a best power mixture setting. To obtain smooth air, all flights were conducted during the early morning hours. To keep from violating reduction procedure assumptions (that the aircraft does not drastically change its weight during the acquisition of data) flights were held to a maximum of one hour. This time limit was deemed necessary to keep the test weight within three percent of the maximum gross weight. (The Cessna 310 aircraft's fuel consumption rate was previously determined to be approximately 24 gallons per hour.) The aircraft was additionally ballasted to produce a maximum weight, maximum forward center of gravity condition. The aircraft loading lessened the effects of inaccuracies in the data extrapolation procedures. The forward center of gravity provided an end of the scale standardization from which to base trim drag effects and is known to be most critical for performance testing. The UTSI level acceleration data were recorded on video tape to acquire the changing parameters that affect performance measurement. The sawtooth climb data were recorded manually due to the long (thirty seconds) data acquisition rate. The total UTSI flight program of eleven flights dedicated 465.5 minutes to sawtooth climbs and 71.8 minutes for level acceleration runs.

VII. FLIGHT TEST SIMPLIFICATIONS AND ERROR ANALYSIS PROCEDURES

To fully comprehend the possible causes of data errors and the reasoning that prompted the suggestion for further testing, a thorough description of the simplifications and assumptions that were used during the flight test program and thesis analysis should be presented.

Of all the parameters that were present during the flight test analysis five variables were believed the most influential to the outcome. These factors in order of believed influence are: aircraft instrumentation and resulting data acquisition, human curve fairing interpretation, actual powerplant horsepower delivery, actual test aircraft gross weight, and pilot technique. It is believed that a distinct breakdown of these parameters would benefit other students and are presented below:

1. <u>Aircraft instrumentation and the resulting data acquisition process.</u>

The UTSI Cessna 310 aircraft is equipped with analog instruments that use either pressures or voltages to measure the performance parameters. Since the majority of the important instruments, (i.e., altimeter, airspeed indicator, and manifold pressure), use pressure variances to determine their readings, it shall be the focus of this section. Whenever dynamic pressure or static pressure are being measured there will undoubtedly be errors from hose lines, internal frictions, and deteriorating calibrations. Because of the instrumentation situation the reading and recording of data were subject to the limitations of the gauge/dial increments, fluctuations from flight vibrations, device frictions and possible "stick points". The precision believed attained for this thesis on instrument interpretation was the following: manifold pressure, RPM, and airspeed meters were distinguishable to two-tenths of each respective unit (i.e., one inch of mercury, one hundred revolutions per minute, and two knots indicated airspeed); the altimeter was distinguishable to ten feet increments over the entire scale; and the air temperature probe to a half of a degree Celsius. This distinguishability is with respect to the

front seat observer and are at least doubled for the rear seat (where the video camera was mounted). These inaccuracies compound the inherent error in the measurement process.

2. Human curve fairing or interpretation.

This condition is in reality an offshoot of the previous problem and its simplification and assumptions. This problem occurs because poor instrumentation and/or data recording could create more highly scattered data points. This increased scatter will demand more subjectively in data fairing and could widen the disagreement of final results. This widening of data scatter could occur because the performance plots are constructed using previous data interpretations (slopes of previous data plots). The use of statistical methods in data reduction would help delineate the nature of this widened disagreement.

3. Actual powerplant horsepower delivery.

As stated in Chapter III, there are basically three approaches to determining the power which an aircraft engine is producing. During this study the method that was used was the engine power chart procedure, chosen because of its ease of use and the fact that the UTSI test organization does not possess engine calibration equipment. These charts are constructed by the engine manufacturers from both actual engine testing and thoery. The charts assume that internal fuel flows to each cylinder are equal and that other variables such as uneven engine cooling and lubrication tendencies are not encountered. In practice, this is not always true, and so these simplifications effect the accuracy of the horsepower available to the propeller. This method is reliable and would only be a factor if engine performance changed from run to run. However, if an engine is not given all the power that is expected, a noncorrelation in data during a test analysis could result.

4. Actual test aircraft gross weight.

To fully understand this simplification it is important that the influence that weight plays in aircraft performance be understood. Since this parameter is addressed within another chapter, it would be advisable to explain how UTSI calculates aircraft total test gross weight. Although several methods are available to account for the varying fuel weight (e.g., fuel metering) the UTSI procedure is to fill the gas tanks at takeoff and to refill the tanks upon test completion. A linear burnoff (i.e., weight reduction) is then assumed. Although this is a common method and usually gives acceptable results, it should be stated that the aircraft is not flown at a steady power setting, and this assumption is a simplification. It should be additionally noted that during the UTSI flight program different individuals filled the tanks. On

one occasion the fuel usage was unusually high suggesting a discrepancy in "top-off" procedures among the attendants. At a weight of six pounds per gallon of aviation gasoline, with the Cessna 310 using an average of approximately one-half gallon of fuel every minute, it is possible to be in total error as much as ten pounds per total weight of 4830 pounds. This will slightly affect data accuracy.

5. Pilot technique.

As previously stated, the sawtooth climb and level acceleration flight techniques attempt to increase the aircraft's total energy by increasing its potential or kinetic energy. Unfortunately, the optimum isolated increase in either altitude or airspeed can be affected by the pilot's flying skill. As inferred earlier, a small tradeoff of height for speed (and vice versa) can misrepresent an actual performance measurement. It is therefore important that a pilot be able to fly a constant speed climb or a constant altitude level acceleration run.

The above mentioned conditions are important factors that should be understood by all students who attempt to undertake a flight test analysis. Although none of these parameters introduce large errors in themselves, the sum of their influence could create relatively substantial errors. These errors lessen data confidence. Following a discussion of terms and definitions, the examination of error analysis is deemed pertinent. As stated by Baird [22], the nature of measurement, in our case flight data parameters, is a procedure which is complicated by the individuality of every experimenter. The exposition of any result can never be termed exact but should be concluded with a restatement of an experimenter's definitions and believed attained precision. This is in direct agreement with Baird's definition that a measurement is "a statement of the results of a human operation of observation." Only after a concerted effort to understand and reduce errors, or non-exactness of observations, should the methods that

estimate the uncertainty of results be implemented and analyzed [23]. Sources of measurement perturbation are categorized into basically two types of errors: random and systematic. Random errors are said to be present when repeated measurements of the same quantity give rise to differing values. Systematic errors are in reference to a perturbation which equally influences all measurements of a particular quantity. While these terms are easily understood, in practice the labeling and reduction of a perturbation is difficult to perform. That is, an error which is systematic under one system of measurement may become apparently random if the mode of interpretation is changed. Baird's factors of limited precision and categorization include:

a) Instrument calibration - systematic

b) Instrument reproducibility - random

c) Observer skill - random

d) Miscellaneous errors such as voltage fluctuations, vibration of instrument supports, etc. - random

e) Fineness of scale division - systematic

As can be drawn from the previous listing of uncertainties, the realistic assessment of errors and their consequences can be monumental. The approach used to examine and quantify the possible errors that have materialized during an experiment include the employment of theoretical distribution curves (e.g., the Gaussian or normal distribution), which rely on a statistical analysis to determine the data variance, standard deviation, and probable errors. These errors are estimated using laws (e.g., chi-square) derived by statisticians from probability

theory that have been thoroughly examined and mathematically modeled. The use of these approaches infer that repeated measurements have been taken and placed within a histogram to demonstrate fluctuations of data. The repeated readings do not necessarily improve the accuracy of the measurement but rather make known an estimate of the precision attained. Ideally, all experimental work should be undertaken only after an understanding of the "error generators" has been solidified. Only when an understanding is accomplished may the researcher weigh, average or reject readings.

An understanding of the problem may be attained from an example. Suppose that a measured flight quantity Z was considered to be a function of total aircraft lift coefficient C_L. That is:

$$Z = f(C_L)$$

Then an estimate of the error:

$$\delta Z = [\partial Z/\partial C_L]\delta C_L$$

requires knowledge of the partial derivatives, $\partial Z/\partial C_L$. The error in C_L can be estimated on the basis of the small angle approximation and the assumption of constant aircraft weight. These assumptions imply that $L = W =$ constant, therefore $C_L \sim V^{-2}$ if V is the flight path velocity.

Continuing the derivation yields:

$$\delta C_L \sim -2V^{-3}\delta V$$

and

$$\delta Z \sim V^{-3}[\partial Z/\partial C_L]\delta V$$

An estimate can then be made of δV from the airspeed calibration error and the instrument reading error. As an example, it is estimated that

$\delta V/V$ was approximately 1.6 knots/100 knots on the Cessna 310 (22UT) aircraft during the test program. Of course the parameter of interest (e.g., Z) could be a function of several variables and may not be completely definable without sophisticated instrumentation. Consequently, it is not possible to precisely define the data scatter band which is believed more prevalent at the lower altitude test runs. Suffice it to say that the errors which present themselves during any measurement are important and difficult to define, and that an error analysis of the flight vehicles owned by the Institute would be a wise investment for further performance or stability tests.

IX. RESULTS

Sawtooth-climb and level acceleration data were collected during the month of August 1985 at the UTSI Flight Test Engineering Facility at the Tullahoma Municipal Airport. After correcting for instrument and position errors using accepted procedures, the Cessna 310 calibrated data spreadsheets were constructed.

Sawtooth data were reduced and plotted with the resulting data displayed as Figures 13-17. As became apparent throughout the entire sawtooth/acceleration analysis, a judicious approach was required when interpreting, weighing or eliminating data points during curve "fairing". The first plots within the sawtooth climb reduction procedure (Figures 13 through 16) displaying Pressure Altitude versus Elapsed Time initiated the requirement to account for the influence of outside variables (in this case wind and changes in velocity). The figures which were used to determine the observed rate of climb (i.e., line slope), demonstrated measured changes in performance when altitude was traded for velocity. The slopes were determined using both manual curve fairing and a numerical linear regression technique. It was found that as much as a ten percent variance in slope determination could be produced with the lower altitudes most susceptible to slope fluctuations. It was also of consequence that a variance in linearity could be perceived between the data acquired from the two pilots, reemphasizing the importance of precise flight techniques. As demonstrated in Appendix A, these results were reduced and expanded to account for equation simplifications. As shown in Figure 17, the Rate

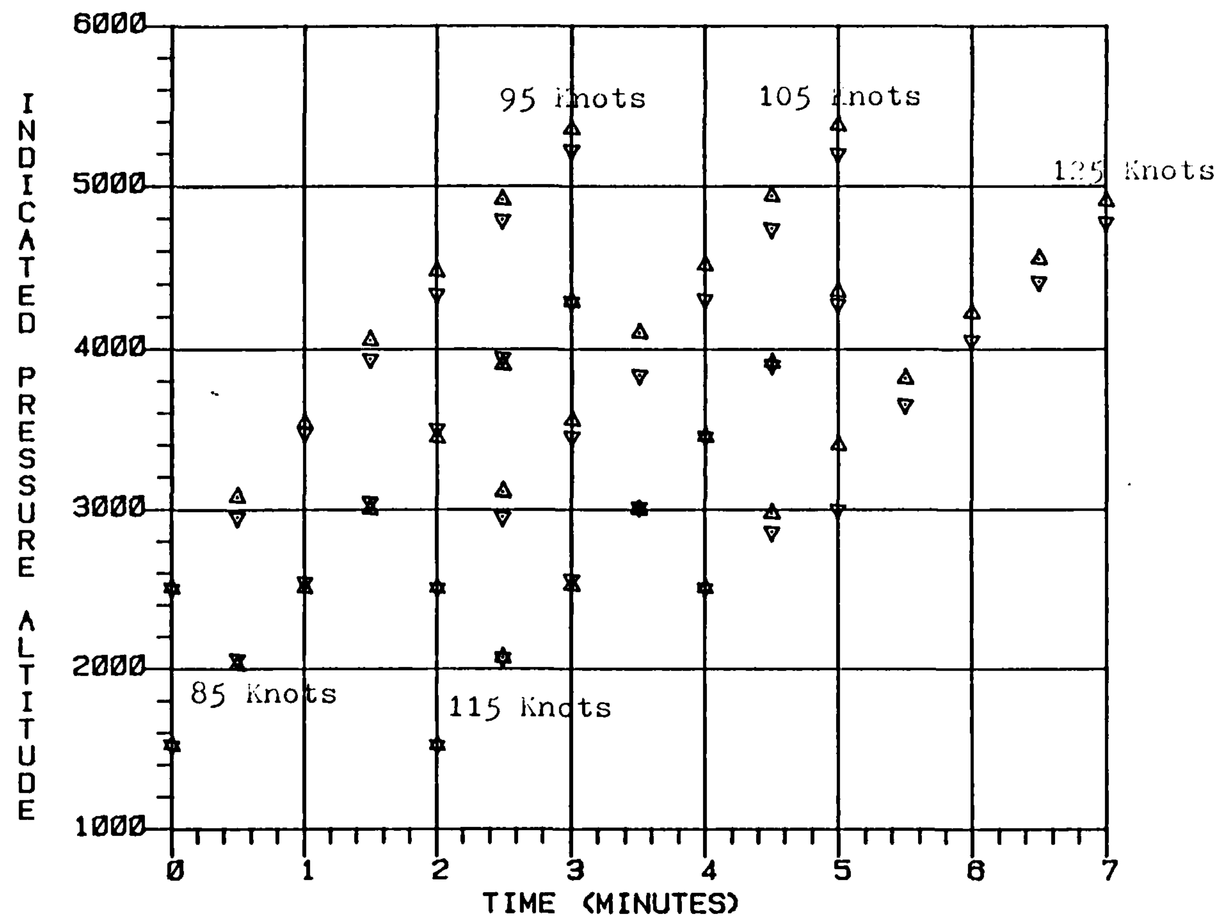

Figure 13. Indicated Pressure Altitude versus Time for 3000 Feet Sawtooth Data

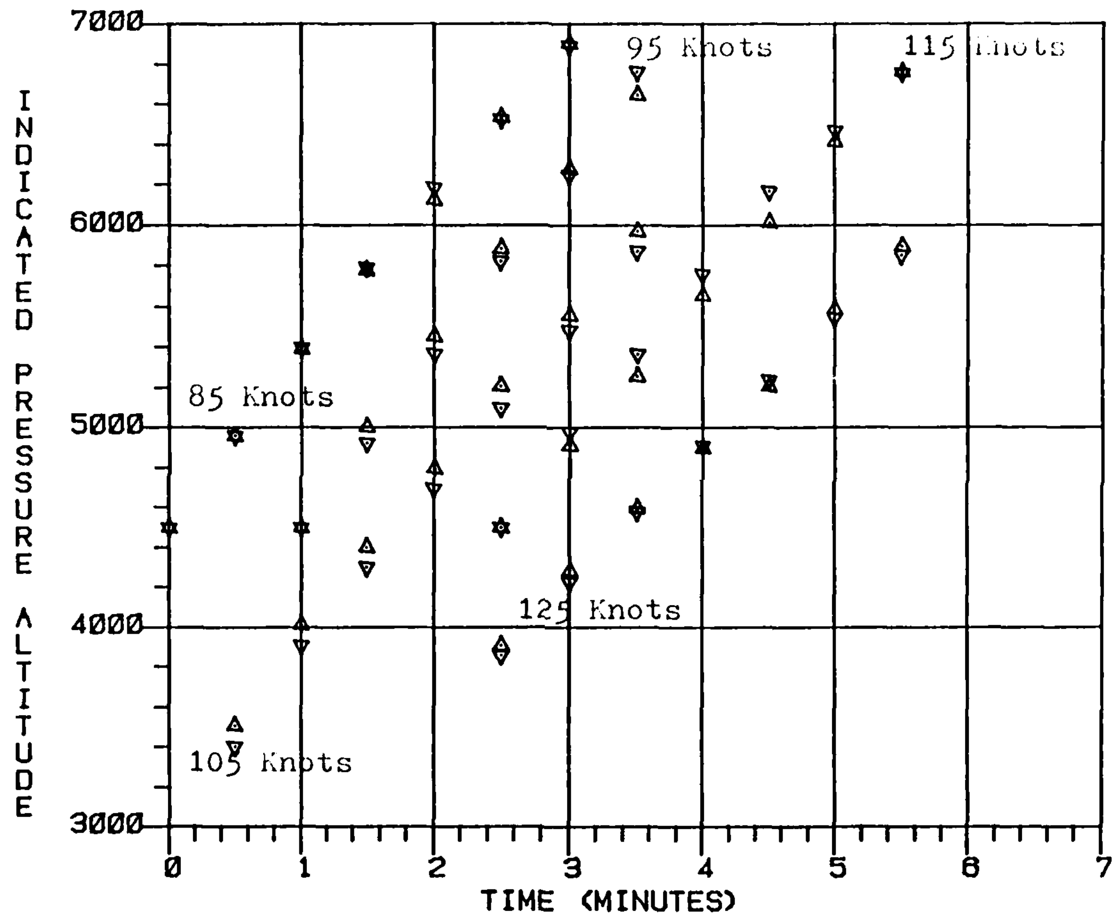

Figure 14. Indicated Pressure Altitude versus Time for 5000 Feet Sawtooth Data

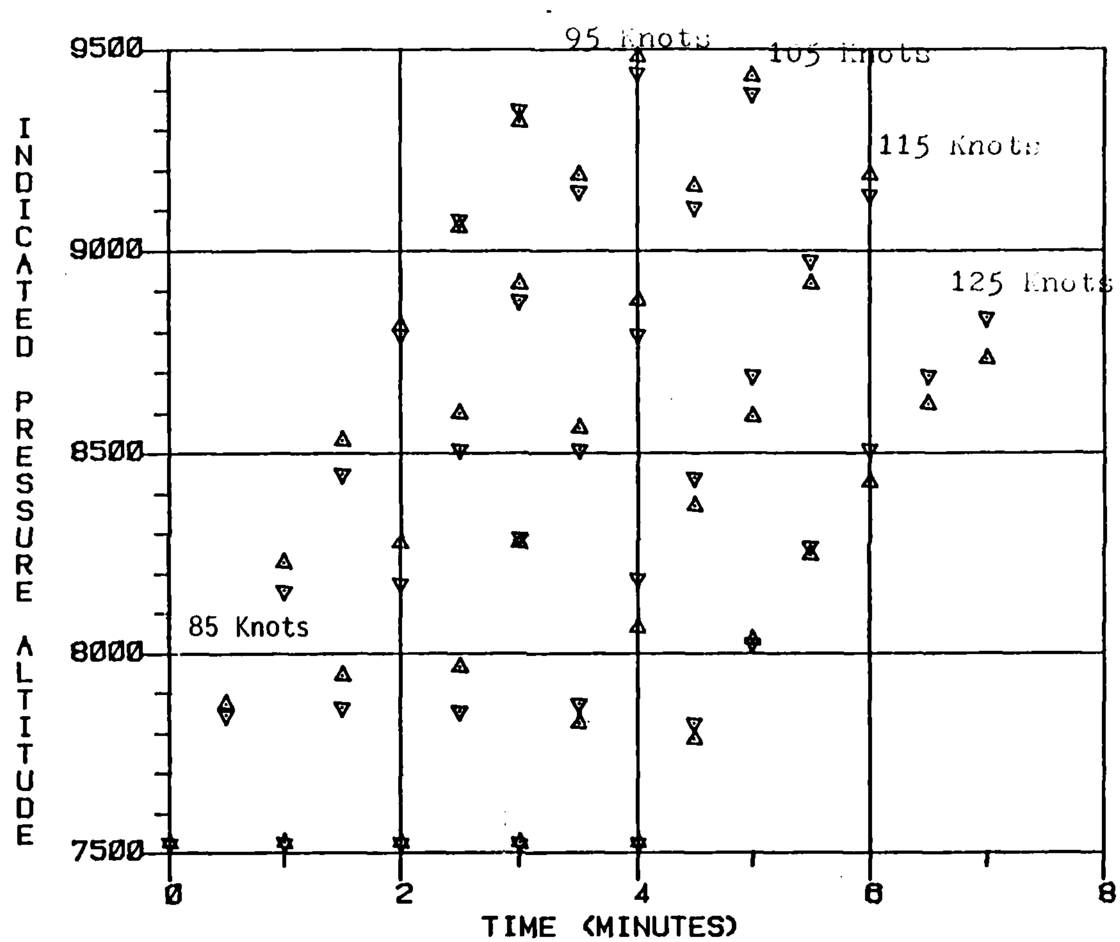

Figure 15. Indicated Pressure Altitude versus Time for 8000 Feet Sawtooth Data

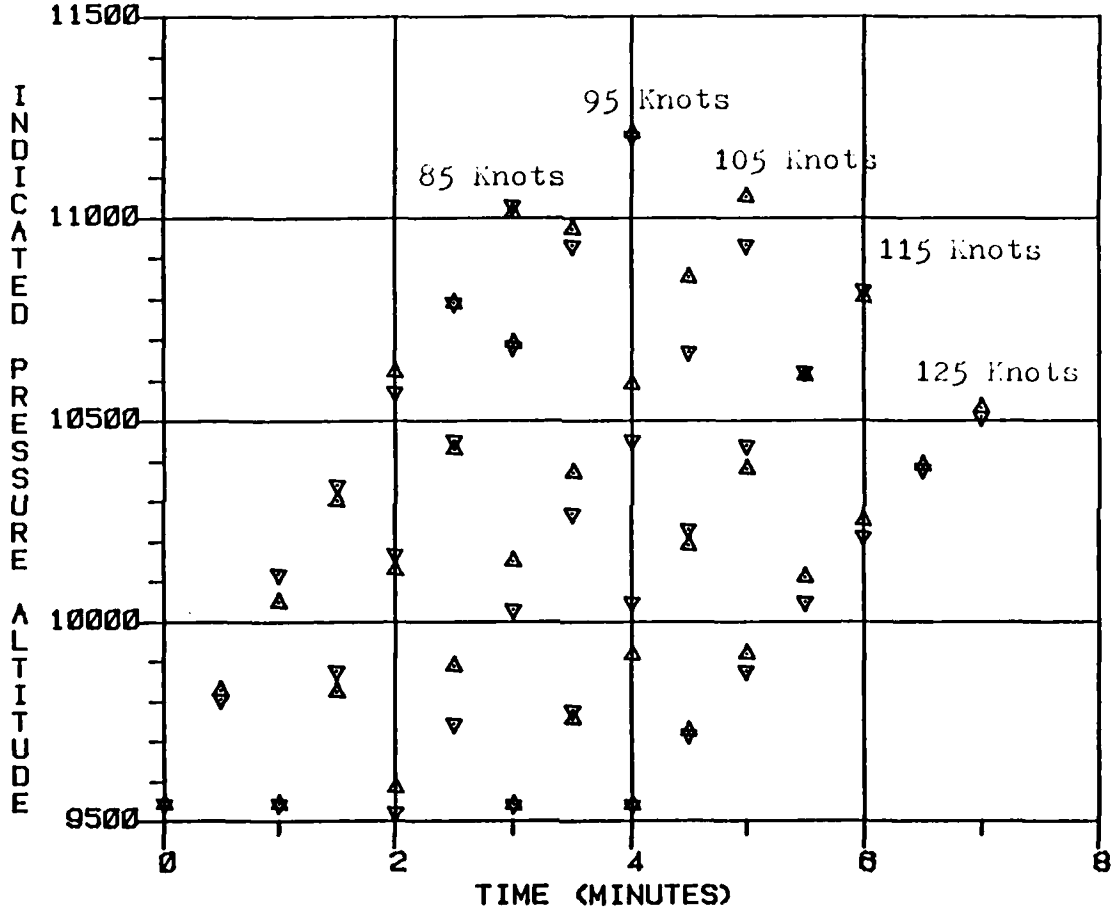

Figure 16. Indicated Pressure Altitude versus Time for 10,000 Feet Sawtooth Data

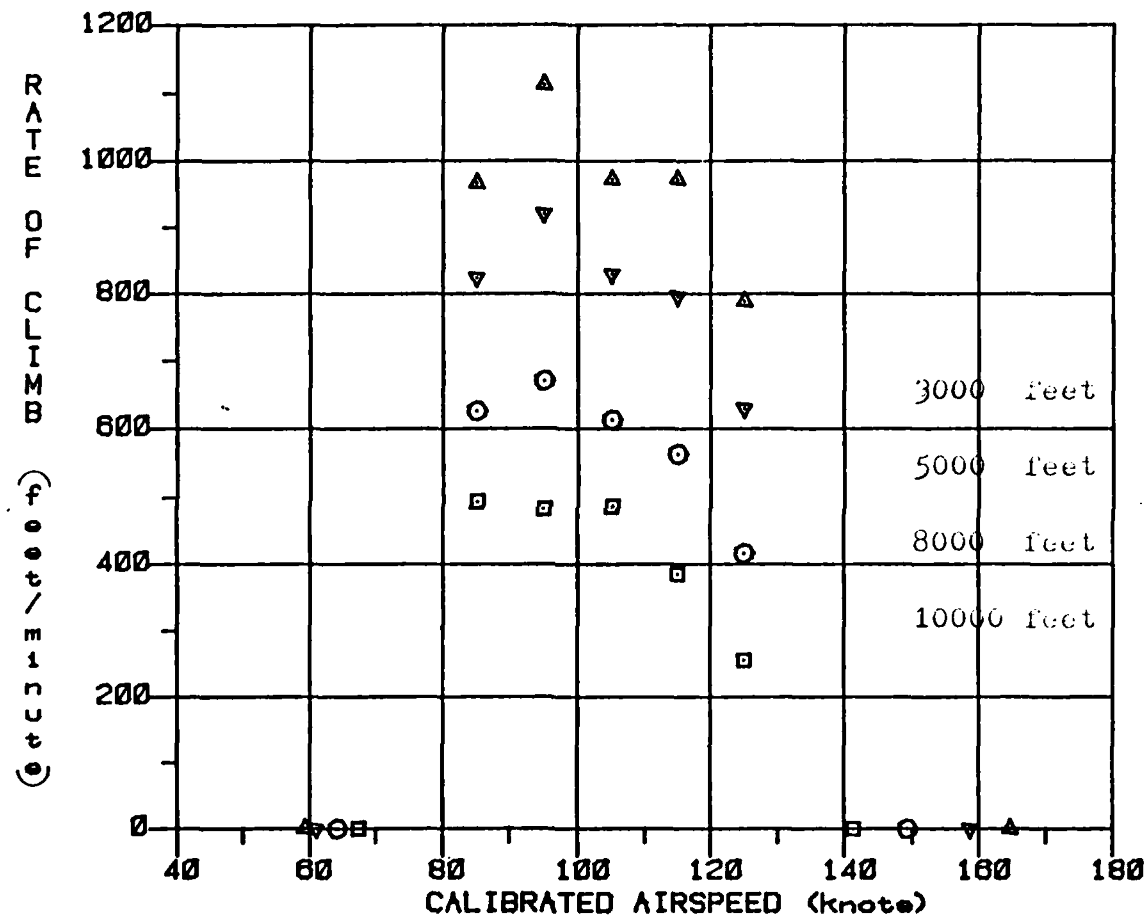

Figure 17. Resulting Rate of Climb versus Calibrated Airspeed Tendencies as Derived from Figures 13-16

of Climb versus Calibrated Airspeed was plotted to enable the maximum climb rate versus airspeed for each altitude to be available for comparison with level acceleration data. Of particular interest in Figure 17 is that while the curve peaks are at expected airspeeds, the two lower altitude bands (the upper two curves) show that 95 knot calibrated airspeed data peaked somewhat higher than expected. Additional scrutiny of raw indicated flight data showed an incremental tradeoff of kinetic energy for potential energy, i.e., the aircraft lost airspeed and exhibited over-optimistic climb performance. This occurrence is important in that it increased the rate of climb by as much as 100 feet per minute. As will be shown, this increase widened the disagreement between the sawtooth climbs and the level acceleration data.

The level acceleration data, as with the sawtooth climb data, were also pivotal on raw data analysis, and it became apparent that plot fairing and interpretation was crucial to producing reasonable results. The initial graphs of True Velocity versus Elapsed Time were highly susceptible to a damped harmonic fluctuation caused by altitude changes as the aircraft was rotated from its near stall condition. This change from a minimum speed/high pitch altitude to a maximum speed/level attitude complicated the fairing of the line slopes. As shown in Figures 18-25 the acceleration term had a wide data scatter band and, as inferred within the development of the governing equations, is the driving parameter in constructing the climb capabilities of an aircraft using a level acceleration technique.

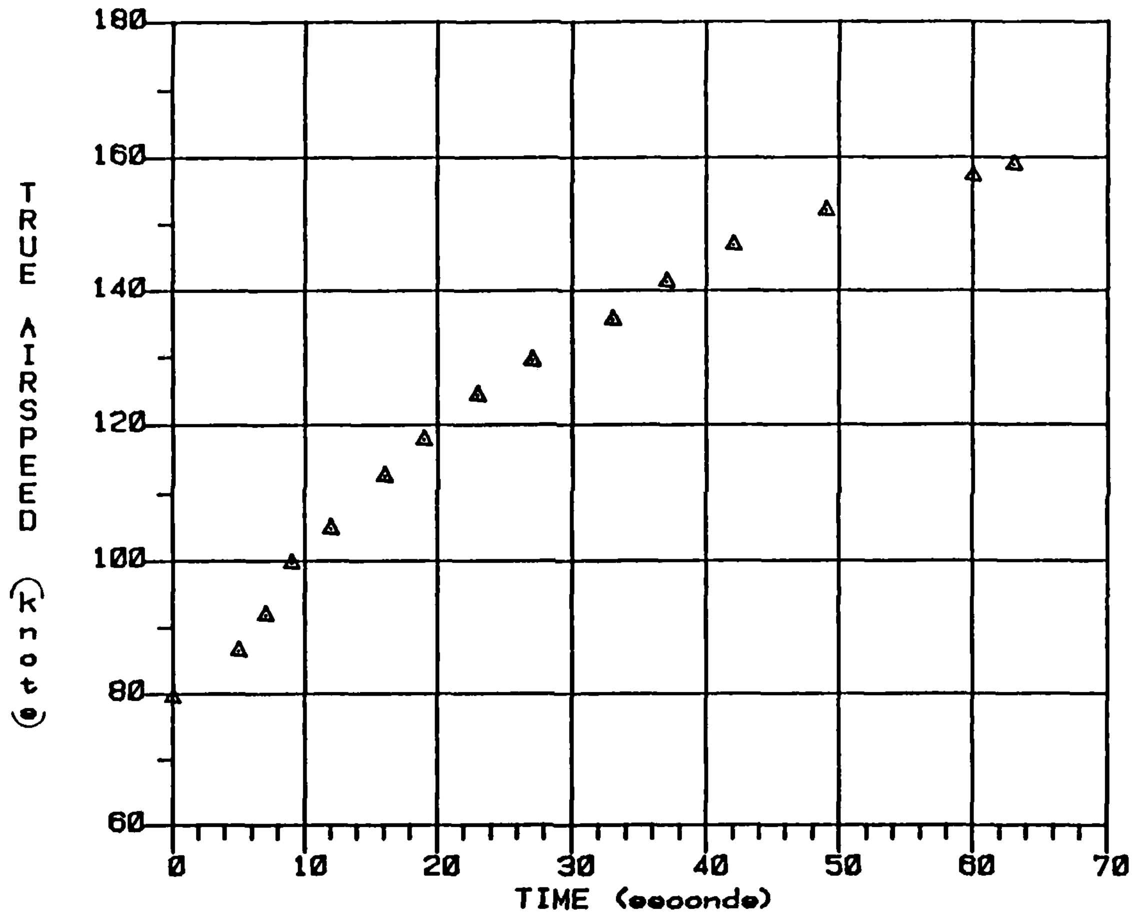

Figure 18. True Airspeed versus Time of Run #1 Level Acceleration Test at 3000 Feet

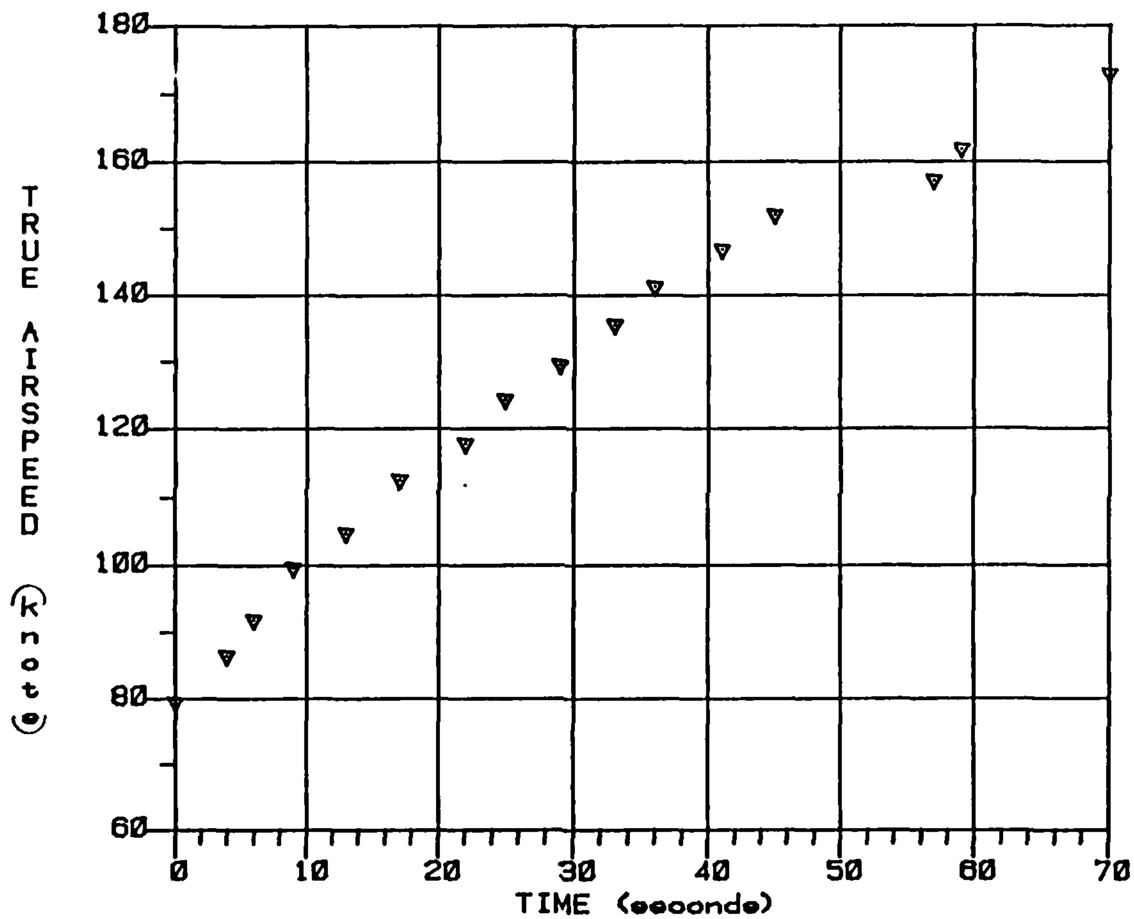

Figure 19. True Airspeed versus Time of Run #2 Level Acceleration Test at 3000 Feet

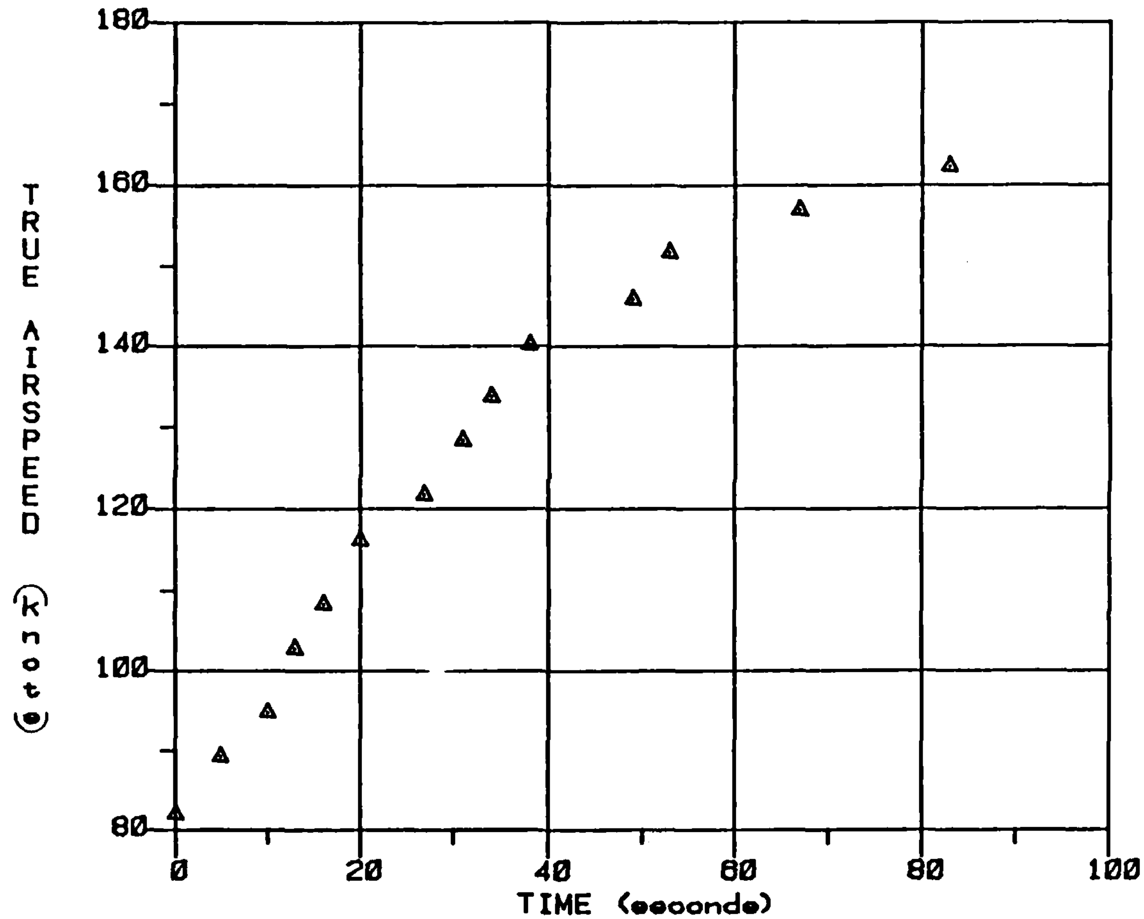

Figure 20. True Airspeed versus Time of Run #1 Level Acceleration Test at 5000 Feet

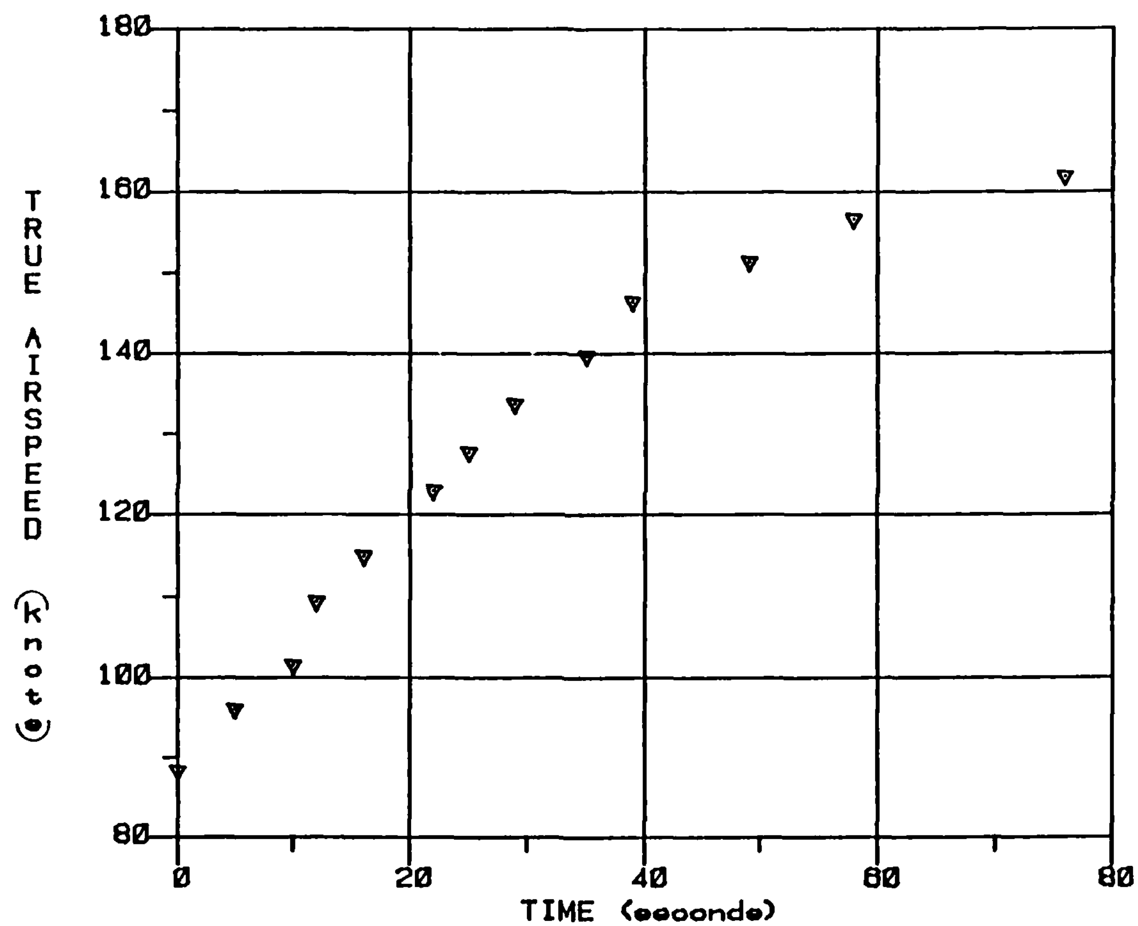

Figure 21. True Airspeed versus Time of Run #2 Level Acceleration Test at 5000 Feet

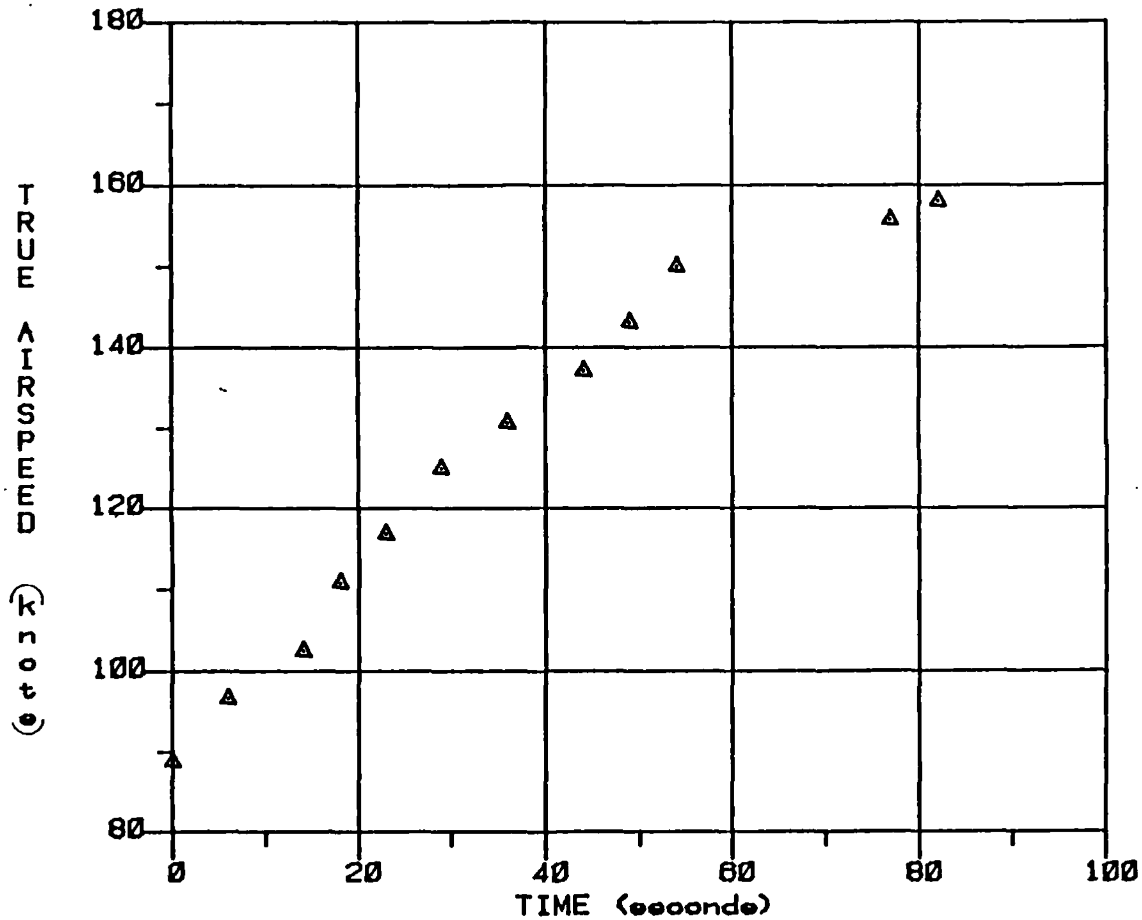

Figure 22. True Airspeed versus Time of Run #1 Level Acceleration Test at 8000 Feet

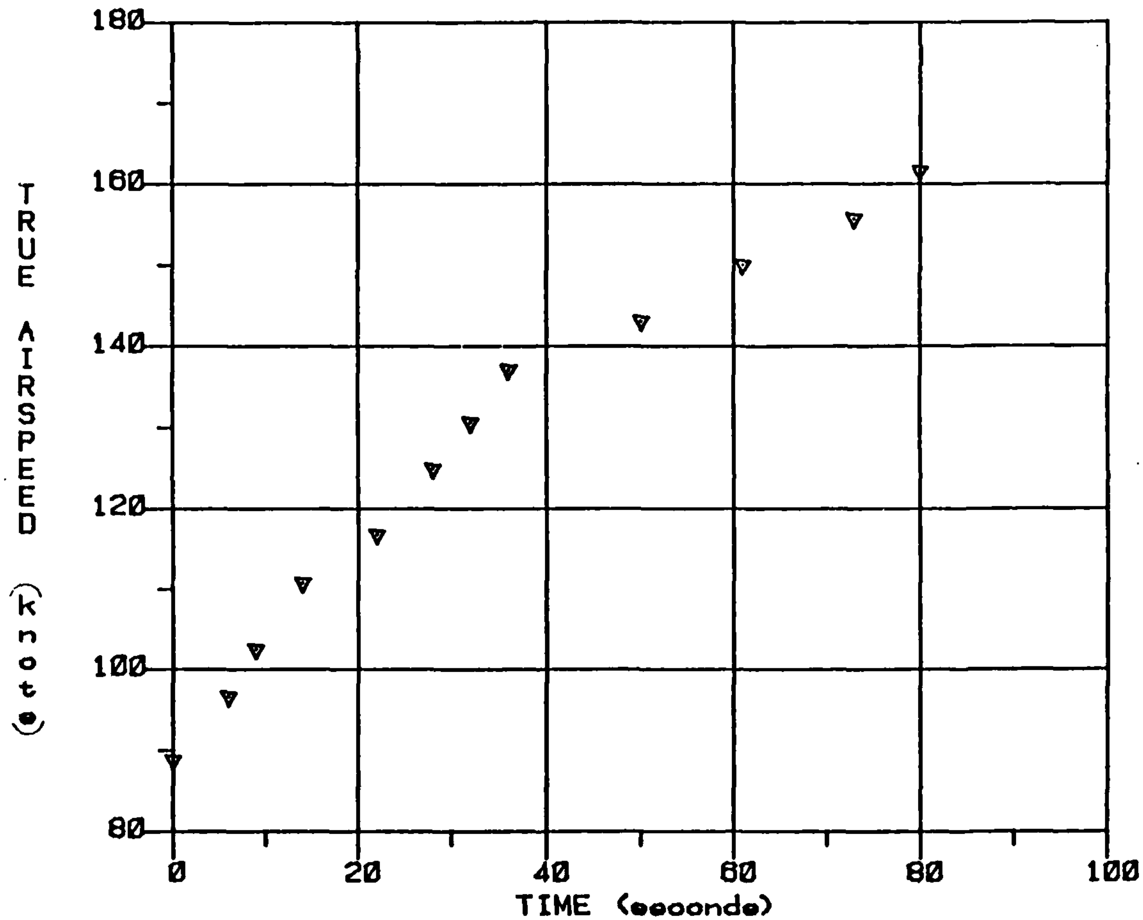

Figure 23. True Airspeed versus Time of Run #2 Level Acceleration Test at 8000 Feet

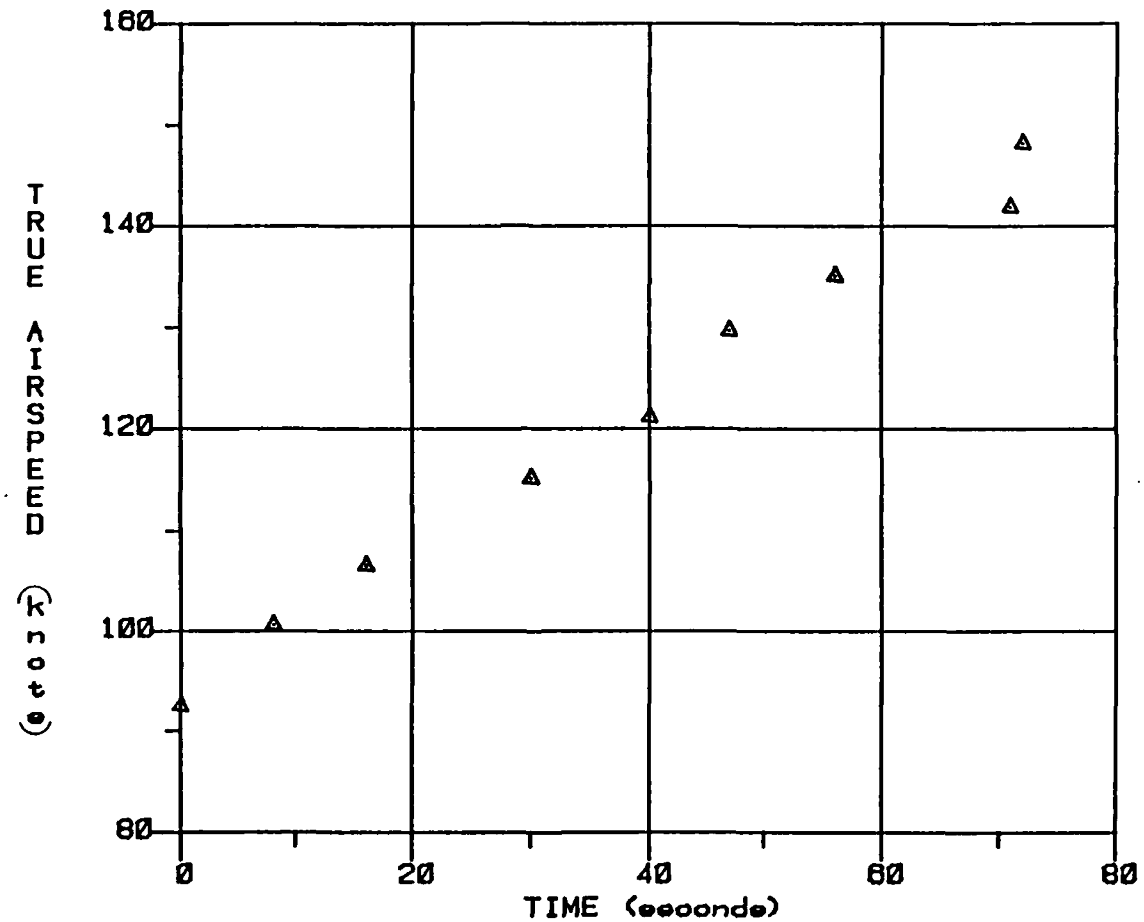

Figure 24. True Airspeed versus Time of Run #1 Level Acceleration Test at 10,000 Feet

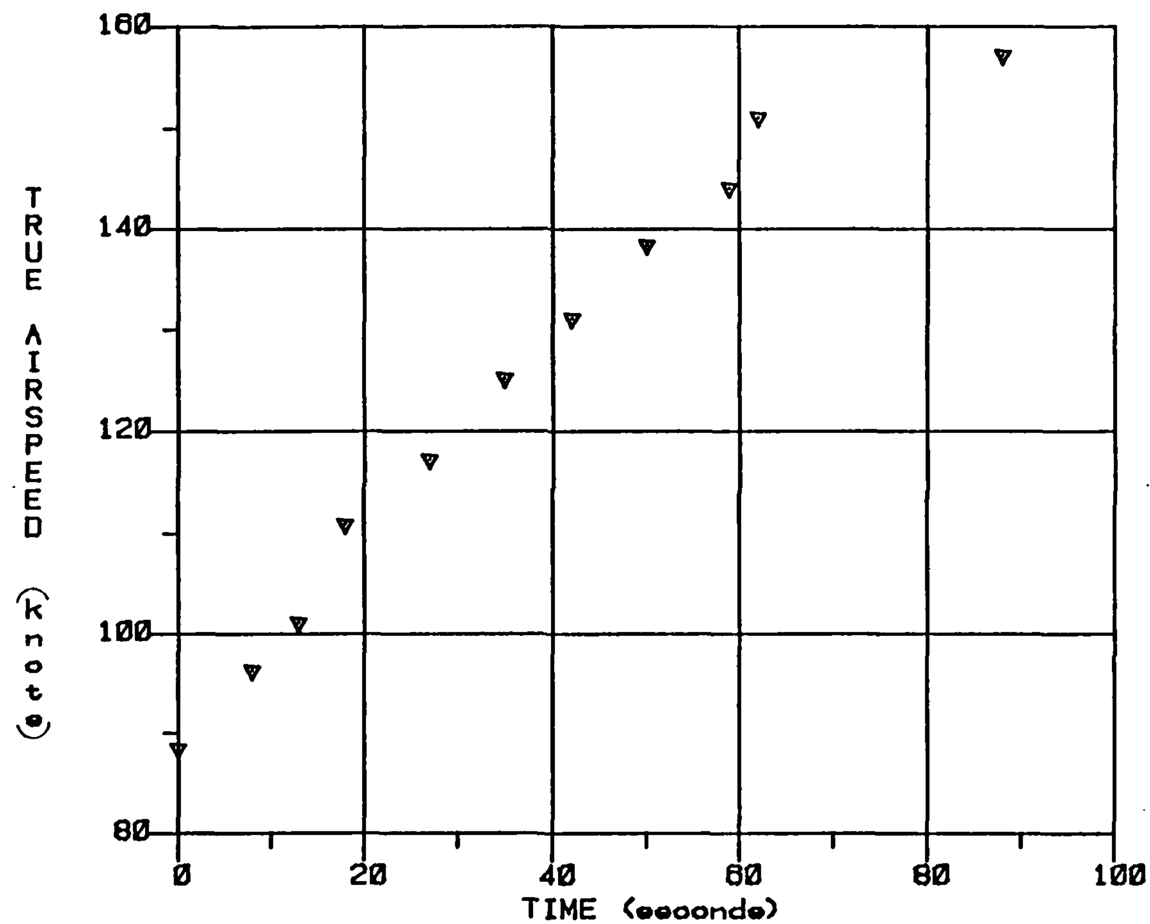

Figure 25. True Airspeed versus Time of Run #2 Level Acceleration Test at 10,000 Feet

As shown in Appendix B the calibrated data were manipulated to provide the Thrust Horsepower in excess from the flight program. As plotted in Figure 26 the corrected power versus calibrated airspeed gave the first indication of the climb performance as provided by the level acceleration method. Of paramount concern within this plot is the substantial scatter of the data, particularly at the lower two altitudes (the upper two curves). This was directly attributable to the higher fluctuations of the lower altitude dV/dt plots. As in the sawtooth procedure, however, this figure provided best rate-of-climb speeds which were reasonable. The maximum weight-corrected Thrust Horsepower in excess from these figures was then manipulated to provide the Density Altitude-versus-Rate of Climb plot of Figure 27. Although a linear regression analysis was used on this figure, it should be understood that a different fairing of the data of Figure 26 would change the climb performance of the aircraft (i.e., the "domino" effect). The resulting comparison of the sawtooth climb to the level acceleration methods is presented on Figure 28. Additionally placed on this plot are the corrected 1958 Air Force flight test data of Reference [16]. Of greatest concern is the lack of correlation of the level acceleration data to either sawtooth climb results. It is felt, however, that the time savings of approximately seven-to-one to obtain virtually the same best rate-of-climb speeds is an important fact that should be well received within the flight test community. What was quite surprising was the correlation between the two sawtooth climb analyses. It should be stated,

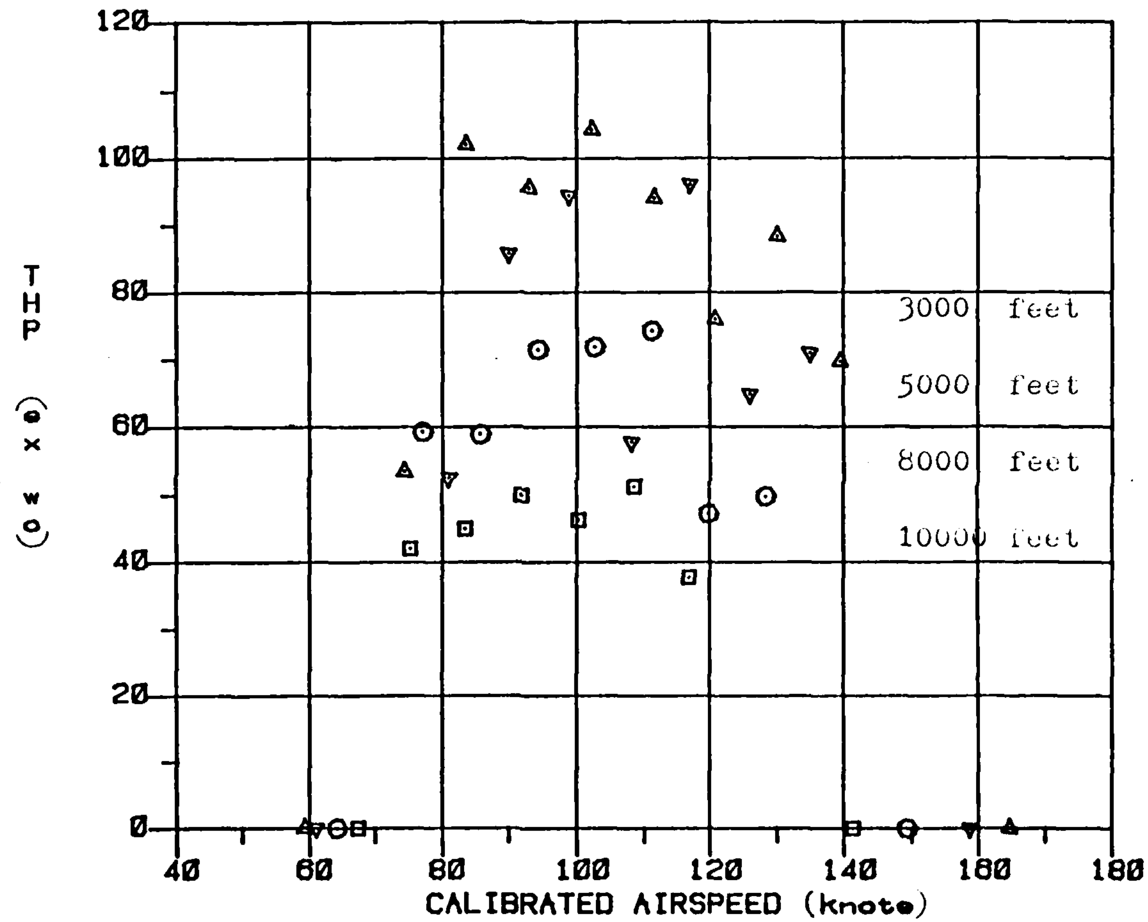

Figure 26. Thrust Horsepower in Excess (Corrected for Weight) versus Calibrated Airspeed as Derived from Figures 18-25

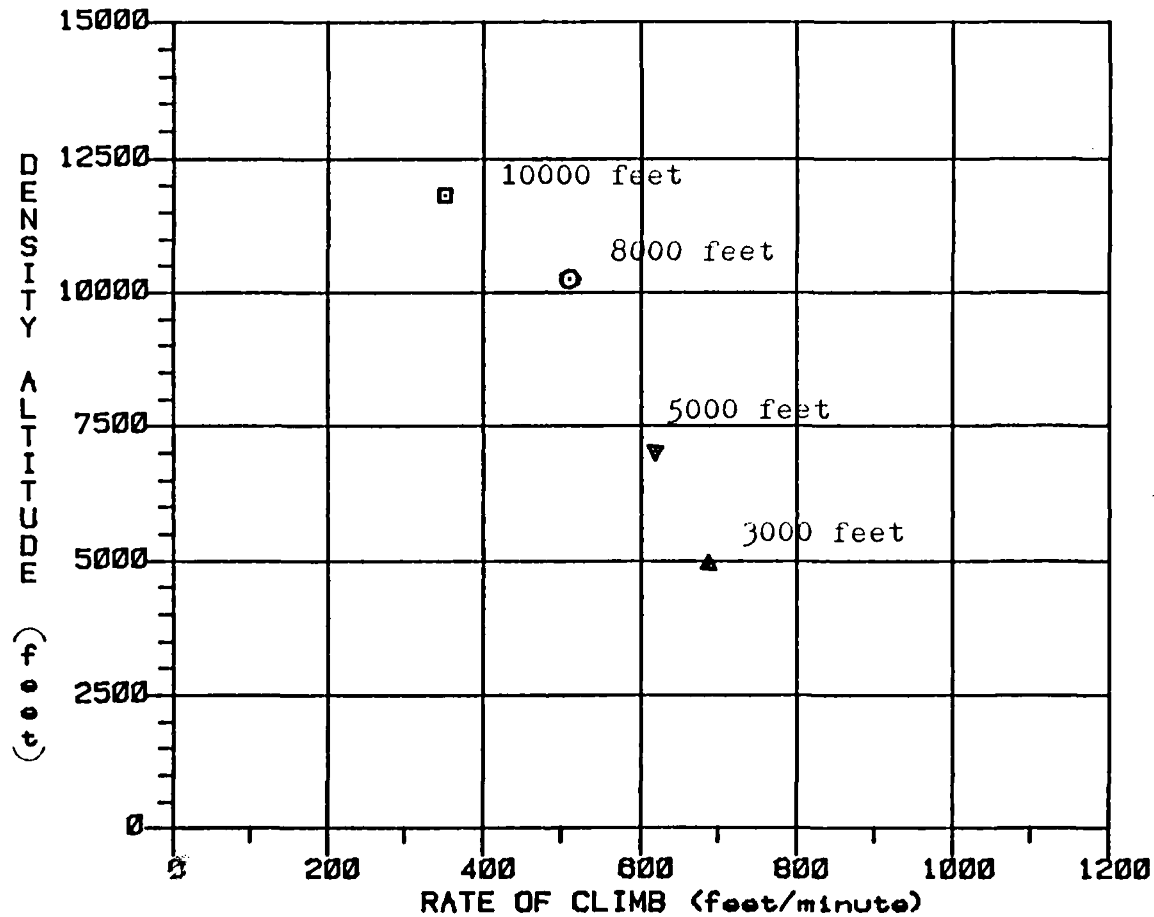

Figure 27.. Density Altitude versus Rate of Climb as Demonstrated by the Level Acceleration Method (Raw Data)

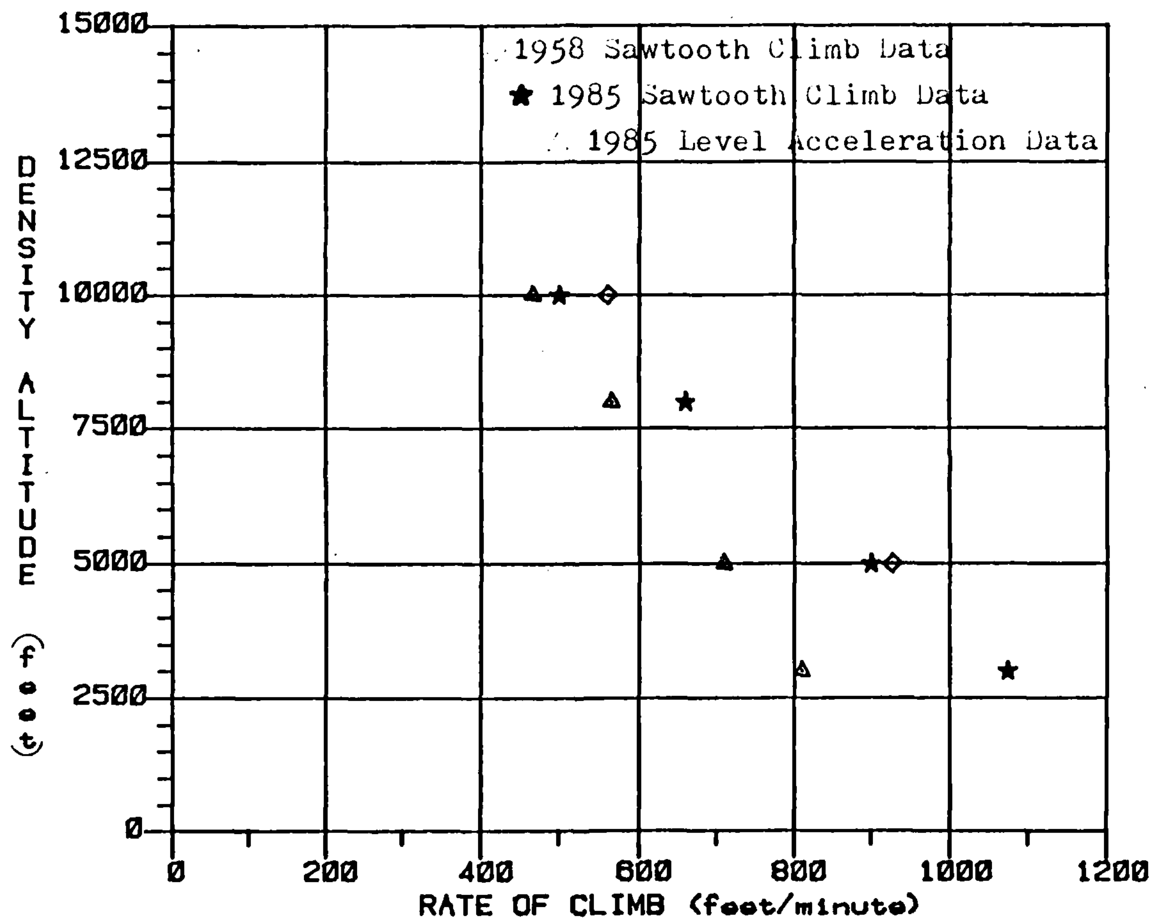

Figure 28. Density Altitude versus Rate of Climb - with Sawtooth Climb and Level Acceleration Results Compared

however, that the twenty-year difference in aircraft ages between the two separate studies caused questioning of the significance of the two climb tests. As inferred within the preceding chapter it is also believed that the test simplifications imposed due to financial and time limitations had the effect of reducing correlation between the energy methods.

Following a detailed examination, it may be stated that the acceleration test is a less accurate procedure for determining the excess power in low thrust-to-weight aircraft due to the following considerations:

1. The sawtooth climb technique eliminates the dV/dt term from the energy equation and measures dh/dt by climbing at constant velocity and constant (full) power engine setting. The drag of the aircraft will then be essentially constant if the altitude change is not too large (i.e., if the Reynolds number change, due to altitude induced kinematic viscosity changes, is small), since the velocity is constant. Also, the drag component due to propeller slipstream will be constant as the engine power and aircraft velocity are constant.

2. The acceleration technique measures dV/dt directly at constant altitude. This is accomplished by increasing thrust horsepower and propelling the aircraft to greater speeds. However, the rapid increase in velocity weakens earlier suppositions, most notably the assumption that propeller efficiency is always at the optimum value. Additionally, the large angle variation(s) of the aircraft with respect to the flight path introduces complications (C_L and drag changes) that may not be discernible with less sophisticated equipment. The increase in speed also changes the aircraft C_L, and therefore, the induced drag is not constant. As V changes, the Reynolds number will also change (creating a non-constant C_D). Lastly, the propeller slipstream is significantly affected by the pitch altitude which implies changes in the slipstream drag. It is believed these influences of increased airspeed and altitude changes make less acceptable the level acceleration flight test method on low thrust-to-weight vehicles.

As discussed previously, it is not possible to completely quantify the errors inherent in the two techniques.

X. CONCLUSIONS AND RECOMMENDATIONS

This thesis has presented an experimental analysis which assesses the accuracy of applying the energy technique to propeller-driven airplanes. The following conclusions were derived from this study.

Conclusions

1) The two methods did not correlate well in the determination of rate of climb. Attributable factors include the flight test simplifications delineated in conclusions 2 and 3. Unaccountable factors include errors from data measurement procedures and incremental losses during the transfer of energy components.

2) Level acceleration data showed large fluctuations in dV/dt during the level acceleration runs. These fluctuations appeared to be caused by:

a. Inadequate instrumentation and ineffective data recording.

b. Failure to account for altitude deviations during the level acceleration runs, and

c. Other factors such as propeller efficiency.

3) This study showed that good pilot technique, and smooth, clear, stable air is essential for performing flight tests of this nature. Unnecessary control deflections and outside energy inputs lessen reliability of performance demonstrations.

4) Confidence in some climb data is low due to an insufficient sample size. Data were collected and averaged from two, opposite-

direction flights at each airspeed and altitude. The impact of a single run was therefore substantial.

5) In spite of the problems enumerated in previous conclusions, the level acceleration technique reduces the flight test time required to determine climb speeds. A time savings of seven-to-one was noted in the comparison of the level acceleration method to the sawtooth climb method. Additionally, the level acceleration method provided a greater amount of performance data.

6) The level acceleration method did show good agreement with the sawtooth climb method when used to determine best rate of climb and best angle of climb speeds. Interpreted data presented a five percent variance in these values.

7) The two methods show better data correlations as the test altitudes are increased. The rate of climb variance at 3000 feet was approximately 25 percent while the variance at 10,000 feet was approximately 5 percent.

Recommendations

Suggestions for improved data correlation include the following:

1) Prior to any future flight tests a thorough error analysis is deemed necessary. The determination of measurement errors for each instrument would enable a reduction of unaccountable data disagreement.

2) It is suggested that for research purposes a more dedicated instrument panel be constructed for level acceleration runs. To help alleviate the large fluctuations in dV/dt during level accelerations

and pin down the actual Thrust Horsepower that is usable for performance, an open or closed loop accelerometer is suggested.

3) It is suggested that all flights be performed at daybreak and every attempt be made to avoid humid and turbulent weather conditions. It is also suggested that one well-experienced pilot fly the entire flight test program.

4) It is suggested that future test programs be undertaken to include more data runs.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Rutowski, E. S., "Energy Approach to the General Aircraft Performance Problem," Journal of the Aeronautical Sciences, Vol. 21, No. 3, March 1954.

2. Lush, K. J., Davy, B., Dommasch, D. O., and Renaudie, J. F., "Total Energy Methods," AGARD Flight Test Manual, Chapter 7, Vol. I., 1954.

3. Bryson, A. E., Jr., Desai, M. N., and Hoffman, W. C., "Energy State Approximation in Performance Optimization of Supersonic Aircraft," Journal of Aircraft, Vol. 6, No. 6, November 1969, pp. 481-488.

4. Anon, "Naval Test Pilot School Flight Test Manual - Fixed Wind Performance - Theory and Flight Test Techniques," USNTPS-FTM-NO. 104, Unclassified Naval Air Test Center Publication, Patuxent River, Maryland, July 1977.

5. Dommasch, D. O., "Data Reduction and Performance Test Methods for Reciprocating Engine Aircraft," AGARD Flight Test Manual, Chapter 6, Vol. I, 1954.

6. Dommasch, D. O., et al., "Performance of Turbojet Airplanes," AGARD Flight Test Manual, Chapter 4, Vol. I, 1954.

7. Zagalsky, N. R., Irons, R. P., Jr., and Lindquist, O. H., "A Graphical Construct of Time Optimal Trajectories," AIAA Paper 72-123, 1972.

8. Schulz, R. L. and Zalgalsky, N. R., "Aircraft Performance Optimization," Journal of Aircraft, Vol. 9, No. 2, January 1972, pp. 108-114.

9. Erzberger, H., Barman, J. F., and McLean, J. D., "Optimum Flight Profiles for Short Haul Missions," AIAA Paper 75-1124, 1975.

10. Ramamoorthy, P., Swamy, M. S., and Sheela, B. V., "Determination of Minimum-Time-Climb Profile of a Military Aircraft by Energy-State Approximation and Constrained Optimization," Proceedings - National Systems Conference, PSG College of Technology, 1977, (G4-1)-(G404).

11. Nichols, M. A. and Hedrick, J. K., "Minimum Time and Minimum Fuel Flight Path Sensitivity," Journal of Aircraft, Vol. 11, No. 6, July 1974, pp. 320-325.

12. Aggarwal, R., Calise, A. J., and Goldstein, F., "Singular Perturbation Analysis of Optimal Flight Profiles for Transport Aircraft," Proceedings-Joint Automatic Control Conference, 1977, pp. 1261-1269.

13. Kelly, H. J., Cliff, E. M., and Weston, A. R., "Energy State Revisited," Presented at AIAA Atmospheric Flight Mechanics Conference, Gatlinburg, Tennessee, August 1983.

14. Boyd, J. R., Christie, T. P., and Gibson, J. E., "Energy - Maneuverability," UNCLASSIFIED extract of SECRET Report APGC-TR-66-4, Vol. 1, March 1966.

15. Zagalsky, N. R., "Aircraft Energy Management," AIAA Paper No. 73-228, January 1973.

16. Davidson, J. D. and Hodgson, W. J., "L-27A Phase IV Performance," United States Air Force Report, Air Force Flight Test Center, Edwards Air Force Base, California, March 1958.

17. Clancy, L. J., Aerodynamics. New York: July Wiley & Sons, 1975.

18. Kimberlin, R. D., Course Notebook - Performance Flight Testing Short Course. University of Tennessee Space Institute Publication, December 1982.

19. Ardema, M. D., "Approximations in the Minimum Time-to-Climb Problem," NASA Technical Memorandum X-62.292, Unclassified Ames Research Center Publication, Moffett Field, California, August 1973.

20. Anon, "Flying Qualities Handbook," USAF Test Pilot School Air Force Flight Test Center Publication FTC-TIH-79-2, UNCLASSIFIED Document Edwards Air Force Base, California 93523, November 1979.

21. McLaren, I., Open and Closed Loop Accelerometers. AGARD Flight Test Instrumentation Series, Vol. 6. London: Hartford House, July 1974.

22. Baird, D. B., Experimentation: An Introduction to Measurement Theory and Experiment Design. New Jersey: Prentice-Hall, Inc., January 1964.

23. Brown, T. B., The Lloyd William Taylor Manual of Advanced Undergraduate Experiments in Physics. Massachusetts: Addison-Wesley Publishing Company, Inc., February 1961.

APPENDICES

APPENDIX A. SAWTOOTH CLIMB REDUCTION AND EXPANSION PROCEDURES

GENERAL CALCULATION (FLIGHT TEST)

Prepared ______ Model Cessna 310 Page 1 of 2

Checked ______ Title PERFORMANCE DATA REDUCTION FOR P_{iw}, V_{iw}, N_{iw}, C_{iw} Test Date August 85

Constant Quantities Notes

Serial Number ______ Test # ______ Flt. # ______

Configuration Sawtooth Climb - 3000, 5000, 8000, 10000 feet

Time In ______ Tach In ______

Time Out ______ Tach Out ______

Flight Time ______ Flight Tach ______

85 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet		5000 feet		8000 feet		10000 feet	
1	V_i	Flight Data	Knots	85	84	85	86	85	86	87	86
2	V_I	Inst. Cal#	Knots	83.75	82.70	83.75	84.80	83.75	84.80	85.85	84.80
3	V_c	Pos. Cal#	Knots	79.55	78.40	79.55	80.70	79.55	80.70	81.85	80.70
4	hp_i	Flight Data	Feet	3000	3050	5760	5770	8500	8420	10250	10290
5	hp_I	Inst. Cal#	Feet	3000	3050	5779	5789	8531	8450	10301	10341
6	OAT_i / OAT_I	Flt&Cal#	o	N/A							
7	t_a	(6) in °C	°C	26	26	20	21	15	14	10	10
8	T_a	273.16 + (7)	°K	299.16	299.16	293.16	294.16	288.16	287.16	283.16	283.16
9	CAT_i / CAT_I	Flt&Cal#	o	N/A							
10	t_{cat}	(9) in °C	°C	N/A							
11	N_i	Flight Data	RPM	2500	2500	2500	2500	2500	2500	2500	2500
12	N_I	Inst. Cal#	RPM	2505							
13	MP_i	Flight Data	In.Hg.	25.2	25.1	22.9	22.9	20.4	20.5	19.2	19.1
14	MP_I	Inst. Cal#	In.Hg.	N/A							
15	Dry/Wet Psy.	Flight Data	o / o	N/A							
16	ΔMP	Psyc. Chart	In.Hg.	N/A							
17	MP eff.	(14) - (16)	In.Hg	N/A							
18	T_s at hp_I	AFFTC H'd'bk	°K		282.17		276.69		271.35		267.72
19	T_{cat}	273.16 + (10)	°K		299.16		293.66		287.66		283.16
20	T_s / T_{cat} (opt)	(18) / (19)	N/D		.9432		.9422		.9433		.9455
21	$(T_s / T_{cat})^{1/2}$	$(20)^{1/2}$	N/D		.9712		.9707		.9712		.9724
22	$HP_{ALT.}$	Eng Chart	HP		402		368		328		306
23	$HP_{TEMP. CORR.}$	(22) x (21)	HP		390.4		357.2		318.6		297.6
24	δ at hp_I	AFFTC H'd'bk	N/D		.8954		.8079		.7289		.6792
25	θ	(8) / 288.16	N/D		1.0382		1.0190		.9983		.9826
26	$\sigma = \delta/\theta$ (opt)	(24) / (25)	N/D		.8625		.7928		.7302		.6912

GENERAL CALCULATION (FLIGHT TEST)

Prepared ______ Model Cessna 310 Page 2 of 2
Checked ______ Title PERFORMANCE DATA REDUCTION FOR $P_{iw}, V_{iw}, N_{iw}, C_{iw}$ Test Date August 85
Constant Quantites Notes
Serial Number Test# Flt. #
Configuration Sawtooth Climbs - 3000, 5000, 8000, 10000 feet
Time In Tach In
Time Out Tach Out
Flight Time Flight Tach

85 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet	5000 feet	8000 feet	10000 feet
27	$(\sigma)^{1/2}$	$(26)^{1/2}$	N/D	.9287	.8904	.8545	.8314
28	W_T	Flight Data	Lbs.	4767.4	4664.1	4719.4	4764.4
29	W_S	Arbitrary	Lbs.	4800	4800	4800	4785
30	W_T/W_S	(28) / (29)	N/D	.9932	.9717	.9832	.9957
31	$(W_T/W_S)^{1/2}$	$(30)^{1/2}$	N/D	.9966	.9857	.9916	.9978
32	$(W_T/W_S)^{3/2}$	$(30)^{3/2}$	N/D	.9898	.9578	.9749	.9935
33	P_{iw}	(23) (27) / (32)	HP	366.3	332.1	279.2	249.0
34	V_{iw}	(3) / (31)	Knots	79.2	81.3	80.8	81.5
35	N_{iw}	(12) (27) / (31)	RPM				
36	$R/C_{i\ obs.}$	Flight Data	FPM	941.5	853.5	628.5	504.5
37	$R/C_{temp\ corr.}$	(36) (8) / (18)	FPM	998.2	905.8	666.3	533.6
38	C_{iw}	(37) (27) / (31)	FPM	893.0	818.2	574.2	444.6
	EXPANSION CALCULATION - STANDARD DAY ONLY						
39	Altitude	Arbitrary	Feet	3000	5000	8000	10000
40	$(\sigma)^{1/2}$	AFFTC at (39)	N/D	.9566	.9283	.8866	.8593
41	MP at (39)	MP vs. hp_z	In. Hg.	25.2	23.5	21.0	19.3
42	W	Arbitrary	Lbs.	1	1	1	1
43	W/W_S	(41) / (42)	N/D	1	1	1	1
44	$(W/W_S)^{1/2}$	$((43))^{1/2}$	N/D	1	1	1	1
45	$(W/W_S)^{3/2}$	$((43))^{3/2}$	N/D	1	1	1	1
46	$BHP_{STD.DAY}$	Eng. Chart	HP	390	354	306	274
47	P_{iw}	(46) (40) / (45)	HP	373.1	328.6	271.3	235.5
48	C_{iw}	P_{iw} vs. C_{iw}	FPM	925	765	555	425
49	R/C	(48) (44) / (40)	FPM	967	824	626	495

GENERAL CALCULATION (FLIGHT TEST)

Prepared ____
Checked ____
Constant Quantities

Model Cessna 310
Title PERFORMANCE DATA REDUCTION FOR
P_{iw}, V_{iw}, N_{iw}, C_{iw}
Serial Number ____ Test # ____ Flt. # ____
Configuration Sawtooth Climb - 3000, 5000, 8000, 10000 feet
Time In ____ Tach In ____
Time Out ____ Tach Out ____
Flight Time ____ Flight Tach ____

Page 1 of 2
Test Date August 85
Notes ____

95 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet		5000 feet		8000 feet		10000 feet	
1	V_i	Flight Data	Knots	95	94	94	95	95	95	94	95
2	V_I	Inst. Cal#	Knots	94.5	93.4	93.4	94.5	94.5	94.5	93.4	94.5
3	V_c	Pos. Cal#	Knots	91.4	90.2	90.2	91.4	91.4	91.4	90.2	91.4
4	hp_i	Flight Data	Feet	4060	3940	5860	5800	8570	8480	10380	10400
5	hp_I	Inst. Cal#	Feet	4060	3940	5881	5820	8601	8510	10431	10451
6	OAT_i / OAT_I	Flt&Cal#	o	N/A							
7	t_a	(6) in °C	°C	23	23	18	18	14	15	10	10
8	T_a	273.16 + (7)	°K	296.16	296.16	291.16	291.16	287.16	288.16	283.16	283.16
9	CAT_i / CAT_I	Flt&Cal#	o	N/A							
10	t_{cat}	(9) in °C	°C	N/A							
11	N_i	Flight Data	RPM	2500							
12	N_I	Inst. Cal#	RPM	2505							
13	MP_i	Flight Data	In.Hg.	24.5	24.7	22.8	22.9	20.4	20.5	19.3	19.1
14	MP_I	Inst. Cal#	In.Hg.	N/A							
15	Dry/Wet Psy.	Flight Data	o / o	N/A							
16	ΔMP	Psyc. Chart	In.Hg.	N/A							
17	MP eff.	(14) - (16)	In.Hg	N/A							
18	T_s at hp_I	AFFTC H'd'bk	°K		280.16		276.56		271.22		267.48
19	T_{cat}	273.16 + (10)	°K	296.16	296.16	291.16	291.16	287.16	288.16	283.16	283.16
20	T_s / T_{cat}(opt)	(18) / (19)	N/D		.9462		.9499		.9428		.9446
21	$(T_s / T_{at})^{1/2}$	$(20)^{1/2}$	N/D		.9728		.9746		.9710		.9719
22	$HP_{ALT.}$	EngChart	HP		392		364		326		306
23	$HP_{TEMP. CORR.}$	(22) x (21)	HP		381.5		354.8		316.5		297.4
24	δ at hp_I	AFFTC H'd'bk	N/D		.8636		.8059		.7271		.6760
25	θ	(8) /288.16	N/D		1.0277		1.0104		.9983		.9826
26	$\sigma = \delta/\theta$ (opt)	(24) / (25)	N/D		.8403		.7976		.7284		.6879

GENERAL CALCULATION (FLIGHT TEST)

Prepared ______ Model Cessna 310 Page 2 of 2
Checked ______ Title PERFORMANCE DATA REDUCTION FOR P_{iw}, V_{iw}, N_{iw}, C_{iw} Test Date August 85
Constant Quantites Notes ______
Serial Number ______ Test# ______ Flt. # ______
Configuration Sawtooth Climbs - 3000, 5000, 8000, 10000 feet
Time In ______ Tach In ______
Time Out ______ Tach Out ______
Flight Time ______ Flight Tach ______

95 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet	5000 feet	8000 feet	10000 feet
27	$(\sigma)^{1/2}$	$(26)^{1/2}$	N/D	.9167	.8931	.8534	.8294
28	W_T	Flight Data	Lbs.	4779.2	4773.5	4681.5	4726.9
29	W_S	Arbitrary	Lbs.	4800	4800	4800	4785
30	W_T/W_S	28 / 29	N/D	.9957	.9945	.9753	.9879
31	$(W_T/W_S)^{1/2}$	$(30)^{1/2}$	N/D	.9979	.9972	.9876	.9939
32	$(W_T/W_S)^{3/2}$	$(30)^{3/2}$	N/D	.9935	.9917	.9632	.9818
33	P_{iw}	23 27 / 32	HP	351.9	319.5	280.5	251.2
34	V_{iw}	3 / 31	Knots	91.0	91.1	92.5	91.4
35	N_{iw}	12 27 / 31	RPM				
36	$R/C_{i\ obs.}$	Flight Data	FPM	971.5	896	662	574.5
37	$R/C_{temp\ corr.}$	36 8 / 18	FPM	1026.7	943.3	702.1	608.2
38	C_{iw}	37 27 / 31	FPM	943.4	844.8	606.7	507.5
EXPANSION CALCULATION - STANDARD DAY ONLY							
39	Altitude	Arbitrary	Feet	3000	5000	8000	10000
40	$(\sigma)^{1/2}$	AFFTC at 39	N/D	.9566	.9283	.8866	.8593
41	MP at 39	MP vs. hp_z	In. Hg.	25.4	23.6	21.1	19.4
42	W	Arbitrary	Lbs.	1	1	1	1
43	W/W_S	41 / 42	N/D	1	1	1	1
44	$(W/W_S)^{1/2}$	$(43)^{1/2}$	N/D	1	1	1	1
45	$(W/W_S)^{3/2}$	$(43)^{3/2}$	N/D	1	1	1	1
46	$BHP_{std.\ day}$	Eng. Chart	HP	394	358	310	276
47	P_{iw}	46 40 / 45	HP	377	332	275	237.2
48	C_{iw}	P_{iw} vs. C_{iw}	FPM	1065	855	595	415
49	R/C	48 44 / 40	FPM	1113	921	671	483

GENERAL CALCULATION (FLIGHT TEST)

Prepared ______	Model Cessna 310	Page 1 of 2
Checked ______	Title PERFORMANCE DATA REDUCTION FOR	Test Date August 85
Constant Quantities	P_{iw}, V_{iw}, N_{iw}, C_{iw}	Notes ______
	Serial Number ______ Test # ______ Flt. # ______	
	Configuration Sawtooth Climbs - 3000, 5000, 8000,	10000 feet
	Time In ______ Tach In ______	
	Time Out ______ Tach Out ______	
	Flight Time ______ Flight Tach ______	

105 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet		5000 feet		8000 feet		10000 feet	
1	V_i	Flight Data	Knots	105	106	107	109	105	105	105	106
2	V_I	Inst. Cal# ______	Knots	105.5	106.6	107.7	109.9	105.5	105.5	105.5	106.6
3	V_c	Pos. Cal# ______	Knots	103.5	104.7	105.9	108.4	103.5	103.5	103.5	104.7
4	hp_i	Flight Data	Feet	4100	3840	4800	4700	8530	8480	10320	10220
5	hp_I	Inst. Cal# ______	Feet	4100	3840	4794	4696	8562	8510	10371	10271
6	OAT_i / OAT_I	Flt&Cal# ______	o ___	N/A →							
7	t_a	(6) in °C	°C	24.5	24.7	21	21	14	14	13	14
8	T_a	273.16 + (7)	°K	297.66	297.86	294.16	294.16	287.16	287.16	286.16	287.16
9	CAT_i / CAT_I	Flt&Cal# ______	o ___	N/A →							
10	t_{cat}	(9) in °C	°C	N/A →							
11	N_i	Flight Data	RPM	2500 →					2520	2500	2500
12	N_I	Inst. Cal# ______	RPM	2505 →					2525	2505	2505
13	MP_i	Flight Data	In.Hg.	24.5	24.7	23	23	20.6	20.7	19.0	19.3
14	MP_I	Inst. Cal# ______	In.Hg.	N/A →							
15	Dry/Wet Psy.	Flight Data	o / o	N/A →							
16	Δ MP	Psyc. Chart	In.Hg.	N/A →							
17	MP eff.	(14) - (16)	In.Hg	N/A →							
18	T_s at hp_I	AFFTC H'd'bk	°K		280.30		278.76		271.26		267.92
19	T_{cat}	273.16 + (10)	°K		297.76		294.16		287.16		286.66
20	T_s / T_{cat} (opt)	(18) / (19)	N/D		.9414		.9476		.9446		.9346
21	$(T_s / T_{at})^{1/2}$	$(20)^{1/2}$	N/D		.9702		.9735		.9719		.9668
22	$HP_{ALT.}$	EngChart	HP		394		364		328		306
23	$HP_{TEMP. CORR.}$	(22) x (21)	HP		382.3		354.4		318.8		295.8
24	δ at hp_I	AFFTC H'd'bk	N/D		.8646		.8400		.7276		.6792
25	θ	(8) /288.16	N/D		1.0333		1.0208		.9965		.9948
26	$\sigma = \delta/\theta$ (opt)	(24) / (25)	N/D		.8367		.8229		.7301		.6828

GENERAL CALCULATION (FLIGHT TEST)

Prepared	Model Cessna 310	Page 2 of 2
Checked	Title PERFORMANCE DATA REDUCTION FOR P_{iw}, V_{iw}, N_{iw}, C_{iw}	Test Date August 85
Constant Quantites	Serial Number Test# Flt. #	Notes
	Configuration Sawtooth Climbs - 3000, 5000, 8000, 10000 feet	
	Time In Tach In	
	Time Out Tach Out	
	Flight Time Flight Tach	

105 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet	5000 feet	8000 feet	10000 feet
27	$(\sigma)^{1/2}$	$(26)^{1/2}$	N/D	.9147	.9071	.8545	.8263
28	W_T	Flight Data	Lbs.	4738.5	4736.1	4723.9	4688.9
29	W_S	Arbitrary	Lbs.	4800	4800	4800	4785
30	W_T/W_S	(28) / (29)	N/D	.9872	.9867	.9842	.9799
31	$(W_T/W_S)^{1/2}$	$(30)^{1/2}$	N/D	.9936	.9933	.9920	.9899
32	$(W_T/W_S)^{3/2}$	$(30)^{3/2}$	N/D	.9808	.9801	.9763	.9700
33	P_{iw}	(23) (27) / (32)	HP	356.5	327.9	279.0	252.0
34	V_{iw}	(3) / (31)	Knots	104.8	107.8	104.3	105.2
35	N_{iw}	(12) (27) / (31)	RPM				
36	$R/C_{i\ obs.}$	Flight Data	FPM	975.5	803	673	496.5
37	$R/C_{temp\ corr.}$	(36) (8) / (18)	FPM	1036.3	847.4	712.4	531.2
38	C_{iw}	(37) (27) / (31)	FPM	954.0	773.9	613.7	443.4
EXPANSION CALCULATION - STANDARD DAY ONLY							
39	Altitude	Arbitrary	Feet	3000	5000	8000	10000
40	$(\sigma)^{1/2}$	AFFTC at (39)	N/D	.9566	.9283	.8866	.8593
41	MP at (39)	MP vs. hp_z	In. Hg.	24.9	23.3	20.9	19.4
42	W	Arbitrary	Lbs.	1	1	1	1
43	W/W_S	(41) / (42)	N/D	1	1	1	1
44	$(W/W_S)^{1/2}$	$((43))^{1/2}$	N/D	1	1	1	1
45	$(W/W_S)^{3/2}$	$((43))^{3/2}$	N/D	1	1	1	1
46	$BHP_{std.\ day}$	Eng. Chart	HP	384	352	306	278
47	P_{iw}	(46) (40) / (45)	HP	367	326.8	271.3	238.9
48	C_{iw}	P_{iw} vs. C_{iw}	FPM	930	770	545	418
49	R/C	(48) (44) / (40)	FPM	972	829.5	614.7	486.4

GENERAL CALCULATION (FLIGHT TEST)

Prepared ______ Checked ______

Constant Quantities ______

Model Cessna 310

Title PERFORMANCE DATA REDUCTION FOR P_{iw}, V_{iw}, N_{iw}, C_{iw}

Serial Number ______ Test # ______ Flt. # ______

Configuration Sawtooth Climbs - 3000, 5000, 8000, 10000 feet

Time In ______ Tach In ______

Time Out ______ Tach Out ______

Flight Time ______ Flight Tach ______

Page 1 of 2

Test Date August 85

Notes ______

115 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet		5000 feet		8000 feet		10000 feet	
1	V_i	Flight Data	Knots	116	116	110	112	112	115	115	115
2	V_I	Inst. Cal#	Knots	117	117	111	113	113	116	116	116
3	V_c	Pos. Cal#	Knots	116	116	109.5	111.7	111.7	114.9	114.9	114.9
4	hp_i	Flight Data	Feet	3000	3020	5640	5740	8340	8410	10140	10180
5	hp_I	Inst. Cal#	Feet	3000	3020	5656	5758	8369	8440	10190	10230
6	OAT_i / OAT_I	Flt&Cal#	o	N/A →							→
7	t_a	(6) in °C	°C	26	26	19	19	14	13	10	10
8	T_a	273.16 + (7)	°K	299.16	299.16	292.16	292.16	287.16	286.16	283.16	283.16
9	CAT_i / CAT_I	Flt&Cal#	o	N/A →							→
10	t_{cat}	(9) in °C	°C	N/A →							→
11	N_i	Flight Data	RPM	2500	2500	2520 →					→
12	N_I	Inst. Cal#	RPM	2505	2505	2525 →					→
13	MP_i	Flight Data	In.Hg.	25.3	25.4	22.9	22.8	20.9	20.6	19.5	19.5
14	MP_I	Inst. Cal#	In.Hg.	N/A →							→
15	Dry/Wet Psy.	Flight Data	o / o	N/A →							→
16	Δ MP	Psyc. Chart	In.Hg.	N/A →							→
17	MP eff.	(14) - (16)	In.Hg	N/A →							
18	T_s at hp_I	AFFTC H'd'bk	°K		282.20		276.84		271.49		267.94
19	T_{cat}	273.16 + (10)	°K		299.16		292.16		286.66		283.16
20	T_s / T_{cat} (opt)	(18) / (19)	N/D		.9433		.9476		.9471		.9462
21	$(T_s / T_{cat})^{1/2}$	$(20)^{1/2}$	N/D		.9712		.9734		.9732		.9728
22	$HP_{ALT.}$	EngChart	HP		404		364		334		314
23	$HP_{TEMP. CORR.}$	(22) × (21)	HP		392.4		354.3		325		305.5
24	δ at hp_I	AFFTC H'd'bk	N/D		.8959		.8102		.7313		.6820
25	θ	(8) /288.16	N/D		1.0382		1.0139		.9948		.9826
26	$\sigma = \delta/\theta$ (opt)	(24) / (25)	N/D		.8629		.7991		.7351		.6940

GENERAL CALCULATION (FLIGHT TEST)

Prepared ______ Model Cessna 310 Page 2 of 2

Checked ______ Title PERFORMANCE DATA REDUCTION FOR $P_{iw}, V_{iw}, N_{iw}, C_{iw}$ Test Date August 85

Constant Quantites Notes

Serial Number Test# Flt. #

Configuration Sawtooth Climbs - 3000, 5000, 8000, 10000 feet

Time In Tach In

Time Out Tach Out

Flight Time Flight Tach

115 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet	5000 feet	8000 feet	10000 feet
27	$(\sigma)^{1/2}$	$(26)^{1/2}$	N/D	.9289	.8939	.8574	.8331
28	W_T	Flight Data	Lbs.	4688.1	4780.7	4746.1	4764.5
29	W_S	Arbitrary	Lbs.	4800	4800	4800	4785
30	W_T/W_S	28 / 29	N/D	.9767	.9959	.9888	.9957
31	$(W_T/W_S)^{1/2}$	$(30)^{1/2}$	N/D	.9883	.9979	.9944	.9979
32	$(W_T/W_S)^{3/2}$	$(30)^{3/2}$	N/D	.9652	.9939	.9832	.9936
33	P_{iw}	23 27 / 32	HP	377.6	318.7	283.5	256.1
34	V_{iw}	3 / 31	Knots	117.4	110.8	113.9	115.1
35	N_{iw}	12 27 / 31	RPM				
36	$R/C_{i\ obs.}$	Flight Data	FPM	931	776.5	557	434
37	$R/C_{temp\ corr.}$	36 8 / 18	FPM	986.9	819.5	588.1	458.7
38	C_{iw}	37 27 / 31	FPM	927.6	734.1	507.1	382.9
EXPANSION CALCULATION - STANDARD DAY ONLY							
39	Altitude	Arbitrary	Feet	3000	5000	8000	10000
40	$(\sigma)^{1/2}$	AFFTC at 39	N/D	.9566	.9283	.8866	.8593
41	MP at 39	MP vs. hp_z	In. Hg.	25.2	23.6	21.2	19.5
42	W	Arbitrary	Lbs.	1	1	1	1
43	W/W_S	41 / 42	N/D	1	1	1	1
44	$(W/W_S)^{1/2}$	$(43)^{1/2}$	N/D	1	1	1	1
45	$(W/W_S)^{3/2}$	$(43)^{3/2}$	N/D	1	1	1	1
46	$BHP_{STD.\ DAY}$	Eng. Chart	HP	392	358	312	278
47	P_{iw}	46 40 / 45	HP	375	332.3	276.6	238.9
48	C_{iw}	P_{iw} vs. C_{iw}	FPM	930	740	500	330
49	R/C	48 44 / 40	FPM	972	797	564	384

GENERAL CALCULATION (FLIGHT TEST)

Prepared ______ Model Cessna 310 Page 1 of 2
Checked ______ Title PERFORMANCE DATA REDUCTION FOR P_{iw}, V_{iw}, N_{iw}, C_{iw} Test Date August 85
Constant Quantities Notes
Serial Number ______ Test # ______ Flt. # ______
Configuration Sawtooth Climbs - 3000, 5000, 8000, 10000 feet
Time In ______ Tach In ______
Time Out ______ Tach Out ______
Flight Time ______ Flight Tach ______

125 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet		5000 feet		8000 feet		10000 feet	
1	V_i	Flight Data	Knots	124.5	125	125	125	124	125	124	124
2	V_I	Inst. Cal#	Knots	125.7	126.3	126.3	126.3	125.2	126.3	125.2	125.2
3	V_c	Pos. Cal#	Knots	125.2	125.9	125.9	125.9	123.7	125.9	123.7	123.7
4	hp_i	Flight Data	Feet	3820	3660	4910	4920	8220	8240	10060	10000
5	hp_I	Inst. Cal#	Feet	3820	3660	4901	4912	8247	8267	10110	10050
6	OAT_i / OAT_I	Flt&Cal#	o	N/A							
7	t_a	(6) in °C	°C	24	24	23	22	12	13	10	10
8	T_a	273.16 + (7)	°K	297.16	297.16	296.16	295.16	285.16	286.16	283.16	283.16
9	CAT_i / CAT_I	Flt&Cal#	o	N/A							
10	t_{cat}	(9) in °C	°C	N/A							
11	N_i	Flight Data	RPM	2500				2550	2520	2520	2540
12	N_I	Inst. Cal#	RPM	2505				2555	2525	2525	2545
13	MP_i	Flight Data	In.Hg.	24.7	24.9	24	24	20.9	20.9	19.6	19.6
14	MP_I	Inst. Cal#	In.Hg.	N/A							
15	Dry/Wet Psy.	Flight Data	o / o	N/A							
16	ΔMP	Psyc. Chart	In.Hg.	N/A							
17	MP eff.	(14) - (16)	In.Hg	N/A							
18	T_s at hp_I	AFFTC H'd'bk	°K		280.76		278.44		271.80		268.19
19	T_{cat}	273.16 + (10)	°K		297.16		295.66		285.66		283.16
20	T_s / T_{at}(opt)	(18) / (19)	N/D		.9448		.9418		.9515		.9471
21	$(T_s / T_{at})^{1/2}$	$(20)^{1/2}$	N/D		.9720		.9704		.9754		.9732
22	$HP_{ALT.}$	EngChart	HP		398		386		340		322
23	$HP_{TEMP. CORR.}$	(22) x (21)	HP		386.9		374.6		331.6		313.4
24	δ at hp_I	AFFTC H'd'bk	N/D		.8720		.8349		.7355		.6855
25	θ	(8) /288.16	N/D		1.0312		1.0260		.9913		.9826
26	$\sigma = \delta/\theta$ (opt)	(24) / (25)	N/D		.8456		.8137		.7419		.6976

GENERAL CALCULATION (FLIGHT TEST)

Prepared ______ Model Cessna 310 Page 2 of 2

Checked ______ Title PERFORMANCE DATA REDUCTION FOR Test Date August 85

Constant Quantites ______ P_{iw}, V_{iw}, N_{iw}, C_{iw} Notes ______

Serial Number ______ Test# ______ Flt. # ______

Configuration Sawtooth Climbs - 3000, 5000, 8000, 10000 feet

Time In ______ Tach In ______

Time Out ______ Tach Out ______

Flight Time ______ Flight Tach ______

125 Knots indicated airspeed runs

No.	QUANTITY	REFERENCE	UNITS	3000 feet	5000 feet	8000 feet	10000 feet
27	$(\sigma)^{1/2}$	$(26)^{1/2}$	N/D	.9196	.9021	.8614	.8352
28	W_T	Flight Data	Lbs.	4697.8	4746.4	4707.1	4734.4
29	W_S	Arbitrary	Lbs.	4800	4800	4800	4785
30	W_T/W_S	(28) / (29)	N/D	.9787	.9888	.9806	.9894
31	$(W_T/W_S)^{1/2}$	$(30)^{1/2}$	N/D	.9893	.9944	.9903	.9947
32	$(W_T/W_S)^{3/2}$	$(30)^{3/2}$	N/D	.9682	.9833	.9711	.9842
33	P_{iw}	(23) (27) / (32)	HP	367.4	343.6	294.2	265.9
34	V_{iw}	(3) / (31)	Knots	126.9	126.6	125.9	124.4
35	N_{iw}	(12) (27) / (31)	RPM				
36	$R/C_{i\ obs.}$	Flight Data	FPM	806.5	627.5	436.5	336
37	$R/C_{TEMP\ CORR.}$	(36) (8) / (18)	FPM	853.6	666.0	458.8	354.8
38	C_{iw}	(37) (27) / (31)	FPM	793.5	604.5	399.1	297.9
EXPANSION CALCULATION - STANDARD DAY ONLY							
39	Altitude	Arbitrary	Feet	3000	5000	8000	10000
40	$(\sigma)^{1/2}$	AFFTC at (39)	N/D	.9566	.9283	.8866	.8593
41	MP at (39)	MP vs. hp_z	In. Hg.	25.5	23.8	21.3	19.6
42	W	Arbitrary	Lbs.	1	1	1	1
43	W/W_S	(41) / (42)	N/D	1	1	1	1
44	$(W/W_S)^{1/2}$	$((43))^{1/2}$	N/D	1	1	1	1
45	$(W/W_S)^{3/2}$	$((43))^{3/2}$	N/D	1	1	1	1
46	$BHP_{STD.\ DAY}$	Eng. Chart	HP	396	362	316	280
47	P_{iw}	(46) (40) / (45)	HP	378.8	336	280.2	240.6
48	C_{iw}	P_{iw} vs. C_{iw}	FPM	755	585	370	220
49	R/C	(48) (44) / (40)	FPM	789	630.2	417	256

APPENDIX B. LEVEL ACCELERATION CORRECTED DATA

FLIGHT TEST DATA SHEET

Date August 85 Model Cessna 310 Ident. No. N 22 UT

Purpose: Level Acceleration - 3000, 5000, 8000, 10000 feet

Fuel ______ gal. L. OB ______ gal. L. IB ______ Gross Wt. ______

______ gal. R. OB ______ gal. R. IB ______ C. G. ______

Config.: ______

Page ______ of ______

Flight No. ______

Time ______ to ______

Total Time ______

Pilot ______

Observer ______

Hpi	Run	Test Weight	Standard Weight	BHP s	BHP t	Average Hpc	θ	δ	σ	$\sqrt{\sigma}$	Density Altitude		
3000	1	4686	4800	198	204								
	2	4673			204								
	Average	4777			204	2990	1.038	.8966	.8636	.9293	4926		
5000	1	4789			191								
	2	4778			190								
	Average	4783			190.5	5000	1.028	.8319	.8094	.8997	7048		
8000	1	4737			165.5								
	2	4722			166.0								
	Average	4730			165.8	8000	1.014	.7428	.7326	.8559	10252		
10000	1	4761	4785	157	157								
	2	4751											
	Average	4756				10017	.9861	.6872	.6969	.8348	11832		

FLIGHT TEST DATA SHEET

Page ______ of ______

Flight No. ______

Time ______ to ______

Total Time ______

Date August 85 Model Cessna 310 Ident. No. N 22 UT

Purpose: Level Acceleration - 3000, 5000, 8000, 10000 feet

Fuel ______ gal. L. OB ______ gal. L. IB ______ Gross Wt. ______ Pilot ______

______ gal. R. OB ______ gal. R. IB ______ C. G. ______ Observer ______

Config.: ______

3000 feet			5000 feet			8000 feet			10000 feet			
Run 1 dV/dt	Run 2 dV/dt	Average dV/dt	Run 1 dV/dt	Run 2 dV/dt	Average dV/dt	Run 1 dV/dt	Run 2 dV/dt	Average dV/dt	Run 1 dV/dt	Run 2 dV/dt	Average dV/dt	True Airspeed
1.33	1.54	1.44	1.54		1.54							80 kts
2.38	2.50	2.44	1.0	1.54	1.27	1.54	1.32	1.43	1.05	1.00	1.02	90 kts
2.44	1.67	2.06	2.70	1.05	1.87	.65	1.90	1.28	.90	1.05	.98	100 kts
2.08	2.00	2.04	2.20	1.55	1.87	1.85	.96	1.41	.63	1.35	.99	110 kts
1.64	1.79	1.69	.85	1.25	1.05	1.35	1.25	1.30	.72	.95	.84	120 kts
1.25	1.28	1.26	1.82	1.39	1.61	.78	1.70	1.24	.85	.87	.86	130 kts
1.11	1.61	1.36	1.10	.91	1.01	1.10	.36	.73	.52	.65	.59	140 kts
.59	1.41	1.00	1.62	.44	1.03	1.00	.55	.77				150 kts

FLIGHT TEST DATA SHEET

Page ______ of ______

Flight No. ______

Time ______ to ______

Total Time ______

Date August 85 Model Cessna 310 Ident. No. N 22UT

Purpose: Level Acceleration - 3000, 5000, 8000, 10000 feet

Fuel ______ gal. L. OB ______ gal. L. IB ______ Gross Wt. ______ Pilot ______

______ gal. R. OB ______ gal. R. IB ______ C. G. ______ Observer ______

Config.: ______

	3000 feet Averaged Runs			5000 feet Averaged Runs			8000 feet Averaged Runs			10000 feet Averaged Runs			
True Airspeed	THP xc	THP $\frac{xc}{wc}$		THP xc	THP $\frac{xc}{wc}$		THP xc	THP $\frac{xc}{wc}$		THP xc	THP $\frac{xc}{wc}$		
80 kts	51.45	53.46											
90 kts	98.08	101.91		52.19	52.46		58.09	59.39		41.67	42.05		
100 kts	92.00	95.60		85.38	85.83		57.78	59.07		44.49	44.89		
110 kts	100.22	104.13		93.91	94.42		70.01	71.58		49.44	49.89		
120 kts	90.58	94.11		57.53	57.84		70.42	71.99		45.75	46.17		
130 kts	73.16	76.01		95.56	96.07		72.77	74.39		50.75	51.22		
140 kts	85.04	88.36		64.56	64.90		46.14	47.16		37.49	37.83		
150 kts	67.00	69.62		70.54	70.92		48.76	49.84					

VITA

Douglas Bruce Youngblood was born in Philadelphia, Pennsylvania on March 27, 1958. He attended elementary schools in that city and graduated from Central High School in June 1976 with an honorary Bachelor of Arts Degree. The following year he entered Embry-Riddle Aeronautical University in Florida with a full Air Force scholarship. In April 1981 he graduated with Distinguished Military Honors, received a Bachelor of Science degree in Aeronautical Engineering, and was commissioned as a Second Lieutenant in the United States Air Force.

After a three year tour of duty at Wright-Patterson Air Force Base in Dayton, Ohio as a research and development officer in Wind Tunnel and Computational Research, he was selected to enter The University of Tennessee Space Institute, Tullahoma, for full-time graduate study. Upon completion of studies in December 1985, Captain Youngblood received a Master of Science degree in Aerospace Engineering and returned to active duty as a military flight test engineer.

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